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Implications of automated vehicles for street design and planning: Espoo case

Thesis submitted for the examination for the degree of Master of Science in Technology.

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Abstract of master's thesis

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Abstract: Automated Vehicles (AVs), in their foundational stage, are gradually emerging into Espoo's road network. During the transition phase, AVs are expected to introduce several challenges and requirements for road operators in design and maintenance of physical infrastructure. This has pushed cities to investigate the potential changes needed to the way their road networks are operated and managed, to consistently support and optimize the outcomes from the introduction of AVs.

The thesis uses a combination of qualitative methods, including map-based survey, road test drives, expert discussions and critical testing scenarios to identify and assess several street design elements in Espoo. The study assesses the automation ability of the Tesla Autopilot in the road network by experimenting several driving scenarios and weather conditions i.e. night and rain. The study also briefly tests other steering assist systems as a way to assess and compare capabilities of other steering assist systems within similar road environments.

Today, the design and quality of road markings are the key features influencing the operation of machine vision based automated systems. Therefore, discussions regarding street design implications are mainly related to the design of longitudinal markings. In this study, several design elements had been identified and studied, including edge marking, lane split and merge marking, bus stop and side parking marking. Based on the current technological trends in vehicle automation, road operators are advised to consider several physical infrastructure and maintenance elements, including primarily the machine readability of line markings. The consistency in design, implementation and maintenance of road markings are seen to have the most benefit in facilitating the deployment of AVs today. However, it was observed that some road marking elements were more critical than others, and therefore, it is suggested that they have higher maintenance and design priority.

While the study assesses street design elements that are seen significant for the operation of steering assist systems today, operators are advised to consider planning frameworks to plan for the introduction of AVs, in order to avoid making changes that may hinder their operation in the future. However, it is important to consider other aspects of road operation and management when considering any new innovative changes in street design in the future.

Keywords: Street Design, Automated Vehicles

Contents

Abbreviations

ADAS Advanced Driver Assistant System

AV Automated Vehicle

ODD Operational Design Domain

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Abdulrahman Al-Metwali

1 Introduction

In cities, motorization has shaped urban development patterns in various ways, ranging from residential parking, built density, expansion of urban development, and street design. On a similar scale, the arrival of Automated vehicles (AVs) is expected to introduce opportunities and threats in the way that it will change cities in the upcoming decades (Mladenovic, 2019; González-González et al., 2019; Stead and Vaddadi, 2019). Different views and scenarios on the direction that the technology will take us to can be found in literature, many of which are concerned with its implications on urban form, others discuss its social, environmental and economic consequences, and more recently, efforts on envisioning its future from an integrated sustainable urban mobility point of view (Backhaus et al., 2019). Cities and regions around the world had recognized the need to cope with this disruption through strategic and scenario planning (City of Toronto, 2019; Traficom, 2019; Austroads, 2017). However, an understanding of the technology as a socio-technical phenomenon with unanticipated consequences is still lacking in some of the planning efforts (Mladenovic, 2019).

Different degrees of optimism and pessimism towards the arrival of AVs have shaped different views on how and why cities should plan for their emergence. On the one hand, there are claims that AVs may have the potential to improve the safety and efficiency of traffic and accessibility of transportation-disadvantaged populations. On the other hand, researchers in urban and transport planning anticipate that AVs will not solve all problems and will probably create new ones, including but not limited to, induced travel demand, the need for vehicle storage as they await users, drop-off zones, and new transportation infrastructure to support its operation (Stead and Vaddadi, 2019). While some of those implications are expected to be visible in the short term, others, including lower vehicle emissions, traveled miles, and traffic congestions, may only become visible when self-driven vehicles are common, shared, affordable and when human-driven vehicles are not present on the roadways (Crute et al., 2018). Today, Partially automated driving systems with features including stop-and-go traffic and lane-keep assist bring more convenience for the driving experience and may, therefore, encourage urban sprawl if not controlled through planning policies. AVs may also have significant consequences on other key planning areas, including infrastructure, transit, public health, and social equity (Crute et al., 2018; Hoadley, 2018). In each of these areas, cities will need to be proactive in capitalizing on the benefits and mitigating the challenges of the technology. It is therefore important at this stage to investigate how such implications can support or threaten strategic urban development policy goals, including mixed-use development, the clustering of urban facilities, the restriction of motorized access in cities, and the adoption of shared high-quality multimodal transport (González-González et al., 2019).

One fundamental challenge in planning for SDV technology in the city is the difference between the dynamics of the development of technology and the built environment, where the latter often having a relatively slower development rate (Mladenovic, 2019). SDV technology, being a socio-technical phenomenon, has various uncertain and unanticipated consequences on transportation planning and policymaking, and to more prominent scale, on the society and the built environment (Blyth et al., 2015). In transportation, the technology can potentially make changes in link and capacity, overall road network layout, street surface and cross-sectional design, integration with other transport modes, parking planning, area and time limitations, travel behavior, and road safety (Stead and Vaddadi, 2019; Hoadley, 2018). From an organizational and political level, the technology may disrupt changes in planning methods, practices, and decision-making processes of infrastructure investments, which can be relevant to municipalities, road operators, and engineering consulting companies (Mladenovic, 2019). Discussions on the disruptions that SDV technology may have on a societal level include changes in perception of safety and security, social division and inequality, employment, and the value of time (Hoadley, 2018; Mladenovic, 2019). Efforts to cope with this disruption had been recognized in several planning efforts, aiming to go beyond the limitations of traditional conventional infrastructural programming practices through several methodologies, including agent-based modeling and network operations planning approach, to help achieve more desirable outcomes (Fagnant and Kockelman, 2014; Austroads, 2017). However, it is important to recognize that emerging technologies such as AVs, usually face the challenge of an institutional void, meaning that current institutions do not have full understanding and control over their outcomes. (Hajer, 2003; Mladenovic, 2019).

Access and ownership are two fundamental factors that will critically define the opportunities or threats that AVs are going to bring to cities (Stead and Vaddadi, 2019). It is important to note that changes in infrastructure will not only be shaped by the technical ability or disability of AVs but will critically depend on the values incentivizing the planning policies with regard to modal priority and vehicle ownership. As shown in Figure 1, in cases where driverless vehicles are not shared and not restricted access to cities, they may cause a decline in active travel and, therefore, an increasing economic, social, and environmental costs. Cities are therefore encouraged to become aware of the foundational knowledge to anticipate the potential societal implications of AVs, and support development and infrastructure investments that ensure attractive, people-friendly, equitable, and safe living environments (Crute et al., 2018). Cities, planning for AVs, are working to develop policies that favor their operation within medium-capacity shuttles rather than personal ownership (Chatman and Moran, 2019).

Along with non-automated, motorized and non-motorized traffic, AVs are expected to share the street space gradually and may, therefore, influence the street environment. One of the potential impacts of AVs towards street design and planning, includes the design of rights-of-way, access and curbside management, street signage and signalization, pedestrian and bicycle crossings (Crute et al., 2018; NACTO, nd). While some design elements are expected to become more relevant in the longer term, others may show more importance in the short term. It is significant to note that implications on street design and infrastructure will not only depend on technical factors as of how AV's (sensors and fusion systems) communicate, perceive and react to the surrounding environment but also on political factors, including for example, what areas and conditions will AVs be allowed to operate in the city (Stead and Vaddadi, 2019; Blyth et al., 2015).

Moreover, advancements in digital infrastructure technology and ITS may also influence the physical street design, for example, by lowering the requirements of the needed physical infrastructure. Nevertheless, such changes require accurate and efficient connectivity between the vehicle, roadside infrastructure, similarly equipped vehicles, and other non-automated transport modes, including walking and biking. Self-driving vehicle technology,

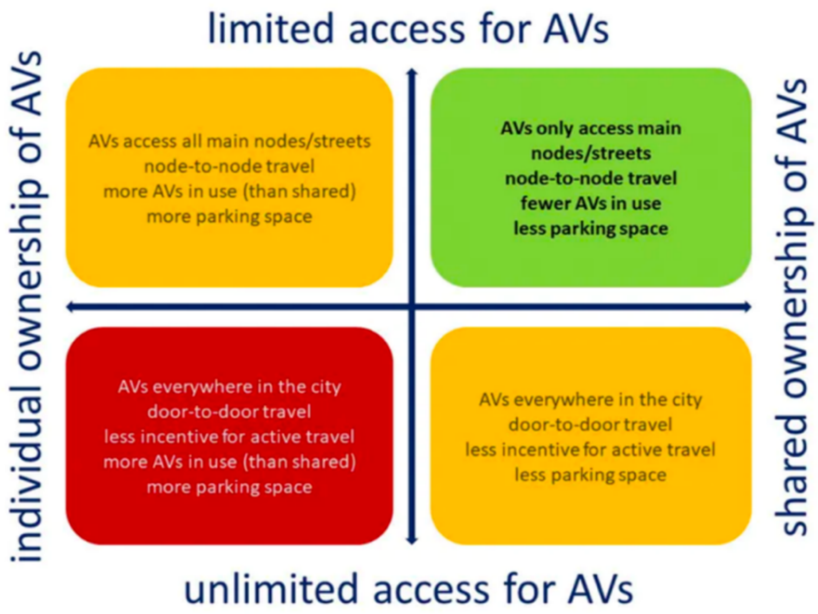


Figure 1: Impacts of different levels of vehicle access and ownership, Diagram by (Stead and Vaddadi, 2019)

in its current stage, is not, and is not expected to be self-contained, self- taught or self-sufficient, but will have to be connected to achieve full-self-driving ability (Stilgoe, 2017). While its ability to classify objects using visual, radar and lidar sensing are impressive, the real advantages are likely to be realized once vehicles can talk to other vehicles and to infrastructure (Dresner and Stone, 2006; Shladover, 2009). However, this requires manufacturers to cooperate with authorities and other vehicle manufacturers to form a systematic intersectorial collaboration. Until private and public collaborations happen on a national and international scale, cities will have to deal with AVs as individual-independent entities.

This study is an attempt to understand the implications of vehicle automation from an early stage on Espoo's street design and planning through a combination of qualitative methods. The motivations of this study is to support the safe and effective operation of AVs in Espoo and achieve an optimised level of mobility benefits. This study will focus primarily on the ability of Tesla Autopilot to understand traffic and the road infrastructure through its camera vision. The overall aim is to be proactive, to maximize opportunities, and to mitigate negative consequences arising from the arrival of AVs in the City. Street design is a complex and systematic area in transport planning, due to the limitations of this study, the methodology in chapter 4 will mostly discuss implications of AVs for physical design elements. The objective of the study is to indicate the capabilities of the currently deployed automated systems in the street environment, and to develop a framework to assess potential changes in road design, maintenance and operation. At this stage, it is challenging to provide practical guidance for cities and road operators in a still-evolving technological environment, and some of the guidance, although seem relevant, could be beyond the scope of individual authorities and operators. However, in recognizing that our current planning methods are not ready to cope with the level of uncertainty and disruption that the technology will bring, we should expect challenges in advancing our planning methods (Mladenovic, 2019).

This study has three main aims:

- Develop automation awareness by understanding the behavior, capabilities, and limitations of partially automated vehicles in different street design and traffic situations in Espoo.
- Develop an understanding of the current situation of street design, road maintenance and operation with regards to vehicle automation.
- Develop an understanding of the emergence of AVs as a socio-technical phenomenon when studying its implications for physical street design, in the context of Espoo.

In the following chapters, this thesis will try to critically frame the challenges that AVs, during the transition phase, will have on physical street design in Espoo. Moreover, it will touch on some aspects regarding the implications of digital street infrastructure based on literature review. Chapter 2 will include a brief background about AVs and review the literature on street design accounting for AVs, published by cities, traffic authorities, and other planning organizations. Chapter 3 will have a brief overview of the street design procedure in Espoo. Chapter 4 will go through the study's methodologies, and findings will be shown in chapter 5. Chapter 6 will include a discussion about the study, as it tries to investigate how considerations regarding vehicle automation may influence street design and planning in Espoo. Chapter 7 will end with concluding remarks about the study.

2 Background

Self-driving vehicle technology, in its foundational stage, exists with varying capabilities and forms (e.g., autopilot systems, automated shuttle buses). Although there had been several trials of highly autonomous bus shuttles in Finland and around the world, its operation is very limited to space, time and speed, due to several technological and infrastructural limitations. Today, commercially deployed automated privately-owned cars are situated on levels 1 and 2 of the levels of automation, as defined by (SAE, 2016), also described as Advanced Driver Assistant System (ADAS). At this level of automation, humans remain fully responsible for performing and monitoring all of the driving tasks. Nearly every car manufacturer and big tech company (e.g., Uber, Google, Tesla) are engaged in autonomous vehicle research with a common goal to go beyond partial automation towards full Self-driving ability. While the timeline for full automation is debated, the transition phase could last from 10-30 years until self-driving vehicles can operate in all driving environments (Milakis et al., 2017). It is, therefore, important for road authorities to become aware and keep track of the capabilities and limitations of automated vehicles, in order to study their implications on street design and other critical areas of planning. Today, the use of automated passenger vehicles is still in the early stages, and its emergence is statically very low. However, it is important to start planning for AVs at an early stage to avoid unconsidered and unplanned outcomes (Blyth et al., 2015). Nevertheless, we should expect that some consequences cannot be assessed quantitatively at this stage of development (Mladenovic, 2019).

2.1 What are automated vehicles (AVs)

An Automated Vehicle (AV) system is a combination of hardware and software that performs the driving function, with or without a human fully monitoring the driving environment. AVs rely upon a variety of sensor technologies and computational power to operate without the control of a driver at varying levels of autonomy. In this thesis, we will use the term (AV) to describe vehicles that have any level of automation and the ability to perform any dynamic driving task. The illustration in figure 2 shows the different hardware and software features and their capabilities. Those features may be fully or partially available in a specific automated vehicle. Unlike CAV (Connected automated vehicles), AVs cannot utilize the connected systems to communicate with other similarly equipped vehicles or road infrastructure and thus cannot automate the responses to associated traffic, weather, or street design conditions. Although connected automated vehicles are anticipated to bring higher benefits than AVs in the traffic environment, it is still not clear how the technology is going to be like and how cities should plan their infrastructure to interact with such vehicles. The vision of an autonomous vehicle – able to navigate the world's complexity using only its sensors and processors is thought to be misleading. AVs will highly depend on social and technical connectivity to effectively operate in complex street environments (Stilgoe, 2017).

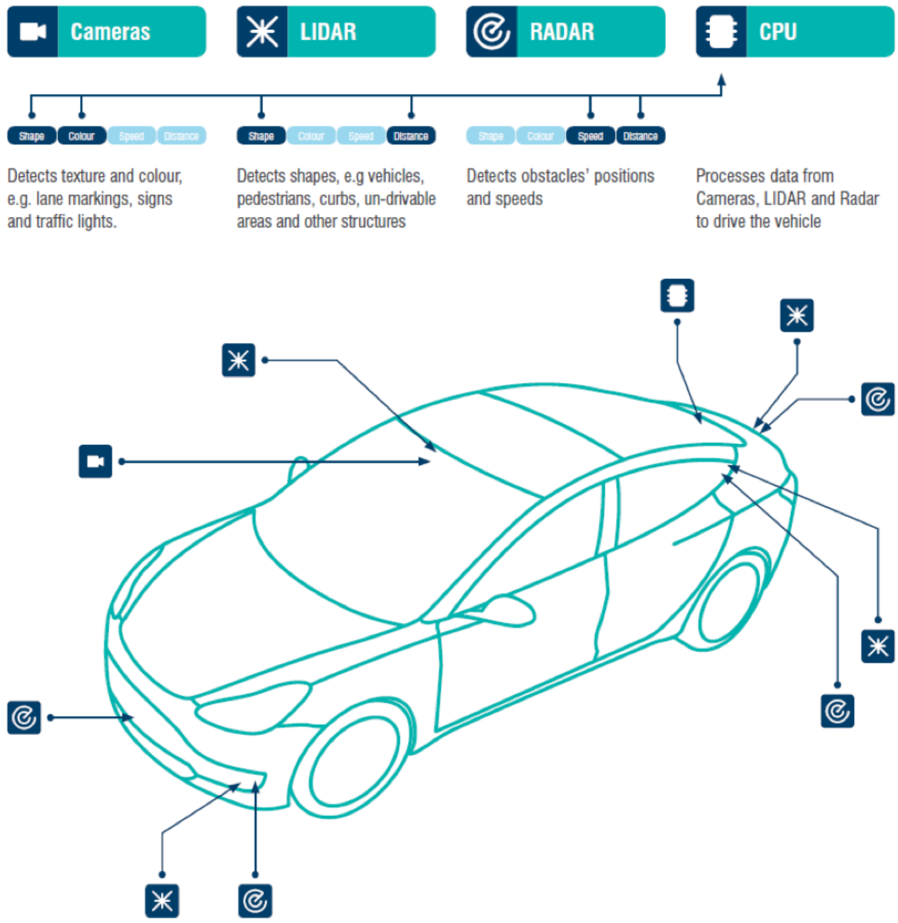


Figure 2: AV hardware features and capabilities

2.2 Levels of automation

Levels of automation, defined by the US Society of Automotive Engineers (SAE), have been adopted in Europe. As mentioned before, some of the lower levels of automation are already available in the market in passenger cars e.g., Tesla, Ford, Volvo, and Mercedes. There are different levels of automated driving; therefore, there has been a need for a standardized framework to describe the capabilities and responsibilities of the different automated systems. Today the dominant framework for understanding the development and operation of AVs is what is called the SAE J3016 Levels of Automation framework. SAE's definition of the automated driving level is based on who does what and when, as shown in figure 3. The lower levels of automation, levels 1 and 2, usually described as partial automation or ADAS, where the human driver is always required to monitor the driving environment, and the system is only meant to support the driving task. On the other hand, levels 3 and 4, sometimes described as highly automated systems, the system is responsible for taking full control of the driving task within specific geographical areas. Although level 3 is considered to be highly automated, it is not considered capable of driving in all road, traffic, and environmental conditions. Therefore, the driver is supposed to be receptive to alert and be ready to serve as a fallback to perform the rest of the dynamic driving task in a very short time notice. However, with Level 4, the system will take care of alert and fallback

SAE level	Name	Narrative Definition	Execution of Steering and Acceleration/ Deceleration	*Monitoring* of Driving Environment	Fallback Performance of *Dynamic Driving Task*	System Capability *(Driving Modes)*
***Human driver* monitors the driving environment**						
0	No Automation	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	Driver Assistance	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes
2	Partial Automation	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/ deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes
***Automated driving system* ("system") monitors the driving environment**						
3	Conditional Automation	the *driving mode*-specific performance by an *automated driving system* of all aspects of the dynamic driving task with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes
4	High Automation	the *driving mode*-specific performance by an automated driving system of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes
5	Full Automation	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**

Figure 3: SAE's framework for driving automation

situations, and the driver is not expected to be receptive. Finally, Level 5, described as full self-driving or fully autonomous, is capable of driving in every traffic, environmental, or street condition. This level of autonomy is not expected to be available any-time in the short term.

In this study, we will primarily focus on the street design implications of partially automated vehicles (SAE Level 2). However, such street design implications may also be relevant in further assessment studies of higher vehicle automation levels. At this level of automation, the execution of both the lateral and the longitudinal vehicle motion control tasks are performed with the expectation that the driver supervises the automation system and take control in the case of any failure, or when the vehicle is driving outside its operating design domain (ODD). Such advanced driver-assistance system features referred to as (ADAS) is offered in different vehicles in the market today, e.g., Tesla autopilot, Volvo pilot assist, Mercedes Drive Pilot, Ford Driver Assist. Different manufacturers use different technologies to help perform the dynamic driving task, some of them only use cameras and radars, e.g., Tesla, while others use more sophisticated and expensive systems such as Lidar, e.g., (Mercedes-Benz, 2019)

Features of currently existing partially automated systems include:

- **Lane Keep Assist (LKA)**: Through machine-vision based lane detection, the system steers the vehicle to ensure the vehicle stays in its lane.
- **Adaptive Cruise Control (ACC):** The system sets a maximum cruising speed but

may adjust speed based on the distance to the vehicle in the front.

- **Traffic Sign Recognition (TSR):** Available in some ADAS systems, the camera is used to detect and read speed signs.

2.3 Operational design domain

The Operational Design Domain (ODD) defines the domain in which the automated system is designed to operate effectively. There are currently no accepted ODD attributes used by traffic agencies and vehicle manufacturers to describe and assess the capabilities of an automated feature/system. (SAE, 2016) notes that the automation level of a driving automation feature and it's ODD, including the conditions under which it is designed to function, are all set by the vehicle manufacturer. It is possible that in the future, users will not be entirely aware of the vehicle's ODD, and if not restricted usage within time-space, it may result in an unsafe traffic environment. Therefore, it is highly possible that in the future, cooperation between vehicle manufacturers and road operators will be realized. With the support of digital infrastructure, vehicle automation systems will only operate within their supported environment to avoid unregulated, uncontrolled, and, most of all, unsafe street environment. (Traficom, 2019) mentions several attributes that are seen to be crucial when defining the ODD, most of which are related to physical and digital infrastructure. Some attributes are static in terms of availability, while others, including traffic, time, and weather conditions, are considered dynamic where up-to-date information is required. It is suggested that in the future, the definition of the ODD should include information about each automated function available in the vehicle. (Traficom, 2019) proposes a framework to define the ODD of a vehicle's automated feature, including information at least on:

- Road type
- Geographic area
- Speed range
- Environmental conditions in which automated vehicles will operate including (weather, daytime/night-time, etc.)

At an early stage of automation, it can be noticed that vehicles of the same described level of automation, have different driving capabilities (Consumer Reports, 2018). Therefore, it is likely that different automation levels and use cases will have different requirements for street design, traffic management, infrastructure, and road maintenance (Austroads, 2017). Limitations in operational domains may also come from factors that affect the system's ability to observe the surrounding environment and therefore make driving decisions — factors including weather, degraded lane markings conditions, and position of speed signs (Transurban, 2018). Road operators may wish to extend the operational domains to improve the operation of automated vehicles. While traffic authorities may not be able to control all the operational domain limitations, they can take steps to modify some of them.

In order to provide equal services to all vehicles, including automated, non-automated, and vulnerable users, ODD management systems may need to be developed, deployed, and operated to support the safe operation of automated systems. An example of an ODD management framework is shown in figure 4. ODD management is expected to influence different areas, including the design of vehicles, system design of traffic management, infrastructure development, and operations of road operators. At the current stage, the concept of ODD management should be established and shared by many players involved in the mixed traffic conditions. This also implies that international collaboration is necessary among automobile manufacturers, network manufacturers and operators, communication industry, governments, and international organizations (Kawashima, 2018), referenced in (Traficom, 2019).

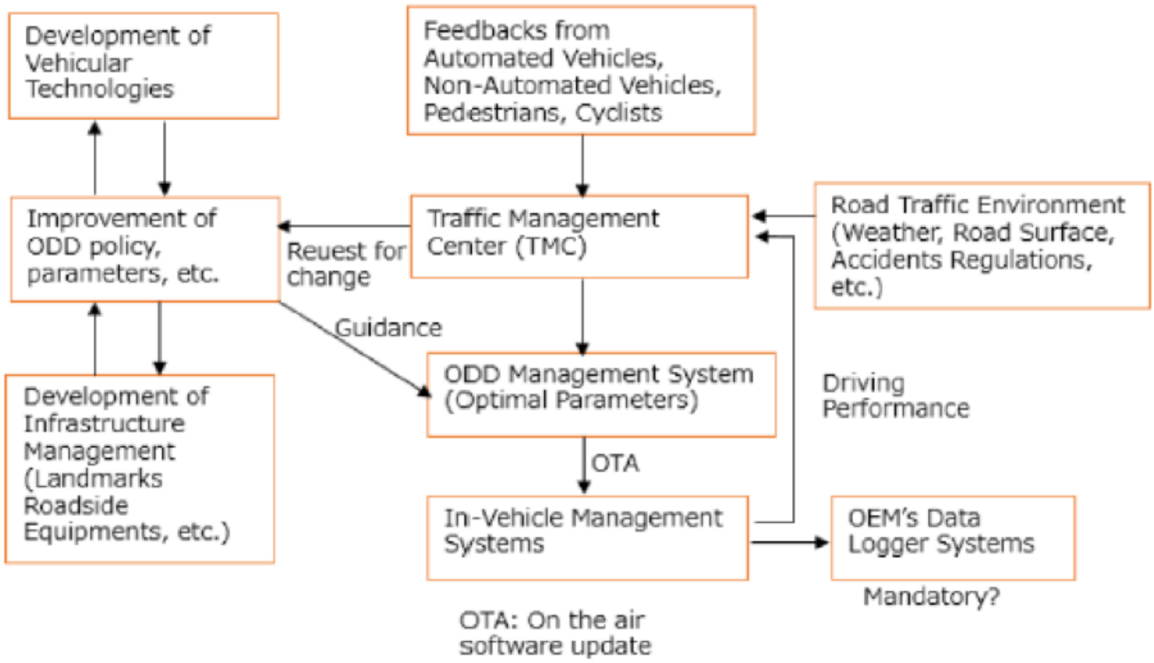


Figure 4: ODD management framework by (Kawashima, 2018), referenced in Traficom (2019)

Today, vehicle operational limitations are broadly stated. For example, the Tesla car user owner manual acknowledges operational limits in weather but does not often give guidance on determining if a particular condition is within those limits. At the same time, national agencies do not yet describe recommended standards in weather limitations for specific vehicles or automation systems. As automation features get to higher levels, there needs to be an objective way to describe the current and forecasted conditions so that they can be compared with the operational design domain of an automation system (Neumeister and Pape, 2019).

2.4 Concepts in street design

Since the introduction of cars, street design has been a matter of disagreement between highway engineers and urban designers (Hebbert, 2005). In conventional urbanism, a street's importance is measured by the height and form of the building frontages, placing high importance on the street environment. On the other hand, conventional highway engineering approached street design through a hierarchical framework, putting more importance on roads with the least buildings and more traffic capacity. Such system provided a basis for standardized classification in design and maintenance at each level of the road network, allocating more resources on points of congestion. Standards for cross-section and geometric design were highly based on the traffic volume and design speed. However, in the last few decades, several planning efforts have taken place, aiming for more equitable, inclusive, and context-sensitive street planning and design. Examples of such planning frameworks include (Aukland Transport; Austroads, 2017). Before we review the literature on street design accounting for AVs, we will first describe concepts in street design that seem relevant to the introduction of AVs. The first describes the importance of integrating vehicle design in infrastructure design in a process called Simultaneous vehicle infrastructure design. The second describes the importance of considering street design in a system's approach.

> Vehicles and infrastructure are integrally related parts of the transportation system. Today, vehicles are designed with a static representation of the infrastructure. Infrastructure is designed with a static representation of vehicles. Transportation system performance can be improved through bringing together the design of vehicles and infrastructure. This process maybe be called, ”Simultaneous Vehicle Infrastructure Design (SVID)” (Albright, 1995)

Today, streets are designed for humans. Street design standards are therefore based on a static assumption of the vehicle and human's visual and reaction capability. Street design elements such as stopping sight distance, road geometry, and readability, are crucial for sustaining a safe street environment. The introduction of automated and connected vehicles is expected to disrupt changes in design standards and incorporate automation-related guidelines (Transurban, 2018). SVID could, therefore, become more crucial with such disruptive change in vehicle automation technology, as the human becomes no longer responsible for making driving decisions. It may, therefore, become more crucial that collaboration between street and vehicle designers should take place to understand how AVs perceive the street environment (Stilgoe, 2017).

> "The separation of functions within and among modes results in denial if not removal of responsibility for the negative system effects of transportation products and services. Public and private transportation investments should be based on system performance, rather than optimizing parts of the system then trying to mitigate unanticipated results that are secondary to the subsystem but primary to a sustainable transportation system. ...There is a need to move from system fragmentation to System Engineering for Transportation." (Roehrig, nd).

Context-sensitive design approach (CSD) is the art of creating public works that meet the needs of users, the neighboring communities, and the environment (Austroads, 2017). This is most relevant to spatial planning, which is based on the concept of integrated land use and transport planning. This integration considers the entire street environment where: planning, implementing, and operating a road should involve the whole street from building line to building line, in an urban context. AVs may have implications on road infrastructure, land use, and other transport modes, it is, therefore, important to consider non-automated vehicle traffic as well as pedestrian and cyclist movements in any future innovative design.

2.5 Literature about street design accounting for AVs

The rapid up-scaling of automated vehicle system technologies presents a change with past patterns of vehicle technology development that has mostly been incremental and focused on relatively well-understood technology platforms. Since the beginning of motorization in the early 20th century, traffic regulations and street design have not been significantly disrupted by new technology arrival and use cases. This is expected to take another turn with the emergence of AVs (International trasport forum, 2018). Cities, traffic, and road authorities around the world are studying the implications of AVs on street design and infrastructure to support the successful integration of automated vehicles as a new transport mode (Traficom, 2019; Austroads, 2017; Transurban, 2018; City of Toronto, 2019). It is until now not clear when, where, what, and how will infrastructural changes take place and what would be their societal impacts. It is also still not apparent how rapidly the technology will evolve, and how much it will be able to adapt to the existing street environment. Moreover, the consequences of a mixed traffic environment where automated and non-automated vehicles co-exist may also influence the way cities will design their streets. Cities are now advised to take the opportunity of introducing automated vehicles in redesigning streets to use space more efficiently than before (Hoadley, 2018).

Austroads (2017) describes a Network Operation Planning (NOP) framework to allow a systematic understanding of the implications of increasing vehicular automation in the road network. The central pillar of the framework is to allow a balanced understanding of the road network between movement and space. The framework proposes a way to strategically assess the implications of AVs in several areas of transport planning, design, and operation. The three-level model promotes holistic consideration for 1) the vehicle (levels of driving automation), by considering the division between human and automated control as a central pillar 2) Interaction with the road environment, considering use cases for interaction between the road system and the AV system, and 3) Strategic management of road use, by considering the concept of movement and place along with the strategic road use hierarchy. Therefore, by determining the needs of street users, the right mix of infrastructural and non-infrastructural solutions, studying the prioritization of interventions, and considering the role of AVs with NOP as a base, it will allow a holistic understanding for the performance and efficiency of the overall street network.

There is a sharp variance in the direction to which cities identify and adopt AV policies when it comes to infrastructure. These approaches reflect mostly on the city's long-term vision for AV integration, and the role of the government in supporting its deployment. There is currently little consensus in terms of what cities should do regarding AVs, while most municipalities have not yet considered AVs in planning. Some agencies are trying to quantify the physical and digital implications on the road environment to provide guidance for road operators on the changes that may be required in road management and infrastructure to support the introduction of AVs. The published reports considering the changes required for street design, from a road operators' point of view, towards physical infrastructure (Transurban, 2018), studies the implications of the operation of machine-vision based driver-assistance systems in a highway road environment, were already deployed AVs are designed to operate. However, other assessment studies consider potential consequences in areas like geometric road design, road maintenance, road operation, and infrastructure planning (Infrastructure victoria, 2018; Traficom, 2019). Moreover, it also assesses other factors, including the impacts of vehicle ownership and mobility. Discussions about AV implications on infrastructure are mostly separated into short- and long-term, where vehicles reach higher levels of automation and connectivity. Therefore, some of the discussed challenges could potentially be addressed later when ITS technology becomes more mature, i.e., Infrastructure to vehicle (I2V), Vehicle to Vehicle) (V2V), and Vehicle to pedestrian (V2P) communications and high precision maps.

Different technological advancements in vehicle automation and connectivity may have different requirements on infrastructure and, therefore, different implications on street design. Already, advanced driver assistance systems, available in some passenger car models, are controlling some dynamic driving functions. At this stage of technology, the human driver is still a significant factor controlling and monitoring all aspects of the driving task (SAE, 2016). On the other hand, Full self-driving vehicles, if and when deployed, will be capable of driving in all conditions without any human interaction. Nevertheless, to reach this level of vehicle automation, connected vehicle technologies will have to enable these vehicles to communicate and coordinate amongst themselves and the surrounding infrastructure, further improving travel safety and efficiency (Stilgoe, 2017). What is between full self-driving vehicles and partial automation is anticipated to, directly and indirectly, affect different levels and aspects of planning. As the technology is in its foundational stage, the critical concerns in design practice should be addressed now (Blyth et al., 2015). A European project, named CoEXIST, developed an "automation-ready framework" to help cities and local authorities to get ready for the transition towards a shared road network with increasing levels of connected and automated vehicles figure 5. The automation-ready implementation framework considers infrastructural, institutional, mobility services, and policy measures.

A pertinent question to cities and road authorities now is whether physical and digital road infrastructure should evolve to support automated vehicles in cities. This, in some cases, will influence or help extend the ODD of some AVs in some parts of the city, depending on where automated driving systems/use cases will be allowed to operate and in what conditions. It is expected that AVs will continue to rely on infrastructure to support its main driving tasks, including positioning, perception, and navigation (Traficom, 2019). Regardless of where the future balance will lie between the vehicle's capability and infrastructure support, it is commonly understood that the two will support each other. A future in which AVs are widespread will require rethinking basic assumptions of traffic operations, safety, and design. Different automation systems use different sensing technologies, each with different levels of capability and use cases. Given much of this is still unknown, designing future road

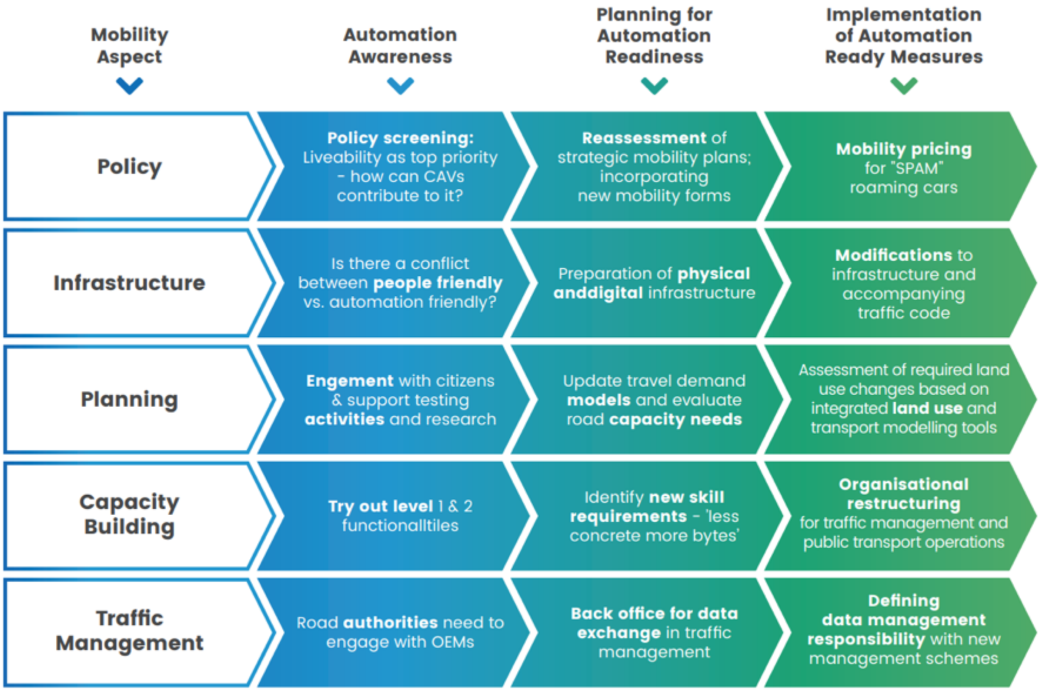


Figure 5: Automation-ready framework, CoEXIST

infrastructure will have its challenges. Advancement of vehicular sensors, cameras, and fusion systems will impact and define their requirements for road infrastructure (Austroads, 2017).

2.5.1 Physical infrastructure

It is still not clear if automated vehicles should cope with any road infrastructure, and if not, what are the requirements for the existing physical infrastructure – including design, planning, operation, and maintenance. This section will outline AV interaction with physical infrastructure and identify how AV deployment may impact road infrastructure in the short and medium-term. The deployment of partially or fully automated vehicles is expected to introduce minimum standards for the road infrastructure. This could mean, e.g., minimum standards for road signs and markings, readability of temporary structures, digital mapping of speed limits (Traficom, 2019). Those are currently seen to hinder the operation of passenger cars with Level 2 automation and are more likely to appear crucial in the short term. (ERTRAC, 2019) advised on the following requirements to support the operation of AVs:

- Clear road and lane markings.
- Adapted and equipped intersections.
- Conditions for dedicated lanes/roads/areas allocated to AVs.
- Management of the changes made to the physical infrastructure and guarantee the level of quality.

The Finnish transport agency's road map and action plan 2016 – 2020 have already discussed updating the design standards for road markings and traffic signs, including guidelines for positioning, readability, and active maintenance to help support the deployment of AVs (Finnish Transport Agency, 2016). The upcoming Finnish traffic legislation will require road operators to switch the currently used yellow line-markings to white, which are seen easier to detect by machine vision. The lifespan of transport infrastructure is usually from 20 to 100 years, thereby any possible changes needed in infrastructure design should be considered as soon as these changes are confirmed to avoid sunk costs (Traficom, 2019). The operation of automated vehicles is expected to become optimal when the roads are planned and designed to accommodate them, however, it is essential to maintain a safe and suitable level of non-automated vehicle compatibility when considering designing road infrastructure for automated vehicles (Austroads, 2017). The human factor and the variability in human driving behavior mean that non-automated vehicle travel on a corridor designed for automated vehicle travel has risks that need to be considered (Infrastructure victoria, 2018). Cities and traffic agencies are, therefore, trying to develop practical maintenance and design guidelines that support the integration of AVs without downgrading the safety of other street users.

Street design

(Austroads, 2017) recommends considering AVs in street design as another mode of transport with a particular set of requirements to interact with the road environment and other road users. They described the implications of AVs on the physical road infrastructure in three main categories:

1. Infrastructure which impacts on the AVs ability to safely position itself and read the road environment. Including: *lane widths, vertical and horizontal curves (which impact forward visibility), intersection design, line marking, and signage.*
2. Structural systems including pavements and structures. Including: *pavement design, barrier design, bridge and culvert design.*
3. Other road design elements or facilities to support AV operation. Including: *considerations for elements such as on-ramps/off-ramps, emergency or pull-off bays, connector roads, merging lengths etc.*

(EuroRAP, 2018) consultation paper described physical and environmental limitations for AVs to be considered by automotive manufacturers. The study was based on lane-keeping systems failure modes and limitations. Such limitations can also be useful for road authorities to allow an understanding of the type of street design features that hinder the operation of AVs. Key limitations (identified as being low, medium, or high impact on vehicle operation) were identified:

- High Factor: Road surface condition (wet, ice, etc.), worn out markings, multiple confusing road markings, old road markings not completely obscured even if blacked out.

- Medium Factor: Road gradient, road curvature, boundaries between multiple lanes.
- Low Factor: Lane width (too narrow, too wide), visibility (e.g., fog).

(Austroads, 2017) describes how the emergence of AVs may influence elements of street design, figure 7. Some of these issues can already be noticed with already deployed level 1 and 2 AVs, while others are expected to become more relevant when AV technology matures enough to be able to correctly read the road environment in a highly reliable and sustained manner. This is expected to be the case when Level 3+ AVs become available, and automated systems have full responsibility for the driving task within their ODD. On the longer-term, more street design aspects are expected to be influenced as well, including but not limited to, lane width and right of way, road geometry, intersection design, parking and kerbside management, pedestrian and bicyclists crossings design, tunnel and bridge design, etc. This can as well be an opportunity for cities to reconsider cross-section design and create more efficient space usage. However, some of those street design features may require vehicle and infrastructure cooperation for efficient and safe operation, for example, due to harsh weather conditions or in complex urban traffic environments.

Design element	Key issues	Modifications AV may require
Alignment	• Stopping sight distance • Horizontal alignment • Superelevation etc.	• Improved ability to read the road with improved headlight technology (e.g. LED, laser light and infrared) and automatic braking systems will change stopping sight distances and vertical curve lengths. • Guidance systems could affect horizontal curve design.
Cross section	• Roadway width and shoulder width, median intersection design, turning lanes.	• Long term changes to vehicle design will change these key requirements e.g. reduced lane widths if vehicles are narrower.
Intersection	• Intersection sight distance models are based on driver behaviour rather than vehicle and roadway capacity	• In the short to medium term seeking to simplify intersection arrangements and interactions between vehicles. In the longer term if there is the greater potential for coordination between vehicles intersections could be made more compact
Structures	• Dynamic loading due to platooning vehicles	• May require a revision of design standards including loading assumptions. Note this may lead to greater numbers of heavy vehicles being attracted to a corridor or provide another reason to use a particular lane as well as decreased spacing between vehicles.
Pavements	• Loading due to platooning vehicles	• May require a revision of design standards including loading assumptions.
Freeways/motorways	• Design of certain aspects of urban freeways/motorways focuses on acceleration lanes, high-occupancy vehicles lanes, and entrance and exit ramps.	• In the long term homogenous fleets of AV will, improve throughput due to certainty of interactions and could require changes to ramp lengths depending on potential light and heavy vehicle platooning requirements. In the short term differences in the level of conservatism of AV operation will impact negatively on road operation, requiring at least current level of infrastructure provision.

Figure 6: Initial considerations for changes to design to encourage the introduction of AV, (Austroads, 2017)

Design of lane marking and road signage

Traffic agencies anticipate that there will be additional requirements from existing planning frameworks and operational guidelines to support AV operations. The readability and constancy of signage and line markings are expected to help support AV operation. Ensuring appropriate signage design and practices for both human drivers and camera vision during the transition phase will require collaboration between both and within the industry and authorities. (Transurban, 2018); (Austroads, 2017), (Traficom, 2019).

- **Road signage**

  Automation related standards regarding the readability and position of road signs are expected to be introduced into the traffic regulations. High consistency in design will be needed to support AVs deployment. It is recommended that the design of signs should consider adding a readability test for future design feedback (Austroads, 2017). In addition to other design guidelines for existing and future street signs, such as height and position, types, and location should be investigated further with cooperation with vehicle manufacturers. Recommended design parameters include:

  - Static signs (Incl. inconsistencies with the design and use of advisory signs, and inconsistencies with the use of words/conditions)
  - Electronic signs (incl. readability of LED signs)
  - Sign location (incl. height of signs)

- **Line marking**

  Road markings are expected to remain crucial for all types of guidance as the traffic gets higher penetration of automated vehicles. It may also increase in importance as more automated vehicles enter the market. (Finnish Transport Agency, 2016; Infrastructure victoria, 2018). This may include investigating the variability and visibility of the existing lane markings and account for the differentiation in driving behavior required, based on double white lines, single lines, or hazard markings. AV technology will benefit from a consistent national approach to line marking to allow consistent and accurate reading of vehicle position on the roadway (Austroads, 2017).

2.5.2 Road maintenance

Vehicle manufacturers are working on developing automated vehicles that can function reliably on today's roads, despite the imperfections of the existing infrastructure. AVs may, therefore, not require significant infrastructure investments until connected and automated vehicles are deployed on public roads. Maintaining and improving the road infrastructure could, however, speed up the deployment process (Public sector consultants and Centre for automotive research, 2017). (City of Toronto, 2019) mentions in their ”automated vehicles tactical plan” that transportation infrastructure providers will need to consider changes to infrastructure based on consumer attitudes related to AVs. With an uptake in AV use, highway authorities will need to understand how these vehicles see – whether that includes updating the maintenance of infrastructure or connected vehicle technology altogether. This is also relevant to harsh weather conditions e.g., snow and fog – and road operators may need to assist these vehicles in seeing better by customizing infrastructure to support its operation.

In mixed traffic, where automated vehicles share the road with human-driven vehicles, inboard systems, will mainly depend on road markings and signs to navigate the road. Therefore, markings, as well as traffic signs, should be in good enough condition to be machine-readable (Infrastructure Victoria, 2018). There are currently no described minimum standards regarding the quality of line markings in the City of Espoo. A European road assessment program named *EuroRAP* published a report, ”A quality standard for road markings and traffic signs”, describing recommendations for visibility and readability in different weather and light conditions based on machine vision automated vehicles. The report emphasizes the importance of lane markings by quoting, ”Lane markings are the rails for the self-steering car”. They anticipate that in the future, minimum standards will be imposed on maintenance guidelines, for example, to guarantee the level of quality of line markings and signs systematically in all the road network (Finnish Transport Agency, 2016). However, such recommendations are based on highway driving environments where current partially automated vehicles are designed to operate. Maintenance of infrastructure will be a key factor during the AV transition phase, and it may become a high propriety obligation for road operators. (The conference board of Canada, 2015).

While some AV manufacturers stated that they would not need lane markings, other manufacturers have suggested otherwise (Mercedes-Benz, 2019). Today, high quality and consistent lane markings are essential for the operation of vehicles that relies on sensors for lane centering. AVs that rely on lane markings for lane centering may not be able to effectively operate in an automated mode if lane markings are not highly clear. Due to different marking materials, methods of application, and stages of the life cycle, there are significant variations in dry night visibility, wet night visibility, and skid resistance (Carnaby, 2003). Potential response on existing marking and signage infrastructure could include incorporating a camera-based drive into maintenance inspections to allow road authorities to determine whether a sign's current location or quality of a lane marking is acceptable for camera vision-based detection system. Line markings may need to be maintained as the default lane use control for the foreseeable future. Human drivers and camera-based driving systems will likely need to be removed from the road system before line marking is made redundant for automated vehicle operations. It is also important to remember that line marking is a road safety issue, not just a road maintenance issue, and for both automated and non-automated vehicles. (Infrastructure victoria, 2018).

2.5.3 Digital infrastructure

The forward development of driving automation systems will likely result in less roadside infrastructure, including road markings and signage. This will become possible when vehicles can utilize connected systems to communicate with the surrounding environment (Infrastructure victoria, 2018). Similar to the physical infrastructure, this change will depend on the types and capabilities of the deployed CAVs. Digital infrastructural changes are expected to fall under several points, including data management, positioning services, mapping, cellular coverage, and communication technologies (Austroads, 2017). Traffic agencies, e.g., Austroads and Traficom, recommend that key data should be digitalized and made available by road operators as electronic regulations. Including data of different street features such as static and dynamic speed limits, accurate speed zone data, road closure, and lane availability, information about clearways, loading zones and parking restrictions, and information about new and changed roads. Those data perhaps do not have to be fully available in the short term, but road operators should be aware that such data is crucial in the future deployment of automated and cooperated systems. The new Finnish road traffic act proposes that geographic information related to all traffic signs, traffic lights, and other traffic control devices be transmitted to an information system maintained by the Finnish Transport Agency to allow there use in digital format in cases such as automated traffic (Ministry of Transport and Communications, 2017). Such information may allow traffic management operations like the one shown in Figure 4 to be realized in the future.

3 Background about Espoo street design

Espoo's centers, neighborhoods, and rural areas are connected by streets of varying designs and levels of quality. Unlike highways, City streets provide multi-modal transport choices and access for all people. Espoo, like other cities, has a very diverse built environment, ranging from rural to urban areas. Street design is, therefore, expected to serve different purposes with respect to its surroundings. Requirements of street design in Espoo are based on three main principles: functionality, comfort, and safety. Street planning environments in Espoo are classified into four different categories 1) compact city areas, 2) residential areas with mainly high-rise buildings, 3) industrial areas, 4) detached house areas (Heli, 2019).

There has not been yet any implemented actions or requirements regarding street design in Finland that considers the operation of AVs in Espoo (Kulmala R., 2019). However, on a national scale, there have been some planning efforts considering automated transport in different modes of, i.e., Road Transport Automation Road Map and Action Plan 2016˘2020, in addition to studies on a European scale on the implications of automated vehicles on roads and traffic. There have been some changes following the European standards in the Finnish national traffic legislation, i.e., switching the color of line-markings from yellow to white for more machine readability. The most recent study on the impacts of AVs had been published by the transport and communication agency in Finland, anticipating the impacts of automated transport on the role, operations, and costs for road operators and authorities in Finland. The report mainly focuses on the implications of highly automated traffic and use cases; however, it also discusses some aspects of street design and planning that AVs may be influenced in the short and medium-term (Traficom, 2019).

3.1 Street typologies

The context of Espoo varies from one place to another and along a given road or street. Environmental features, land uses, density, and travel characteristics shift along a road or street from one side of the city to the other. The functions of a street can change, depending on the different activities and priorities of the surrounding communities. Street design characteristics and requirements are highly based on its context in the built environment. However, there is currently no commonly used framework to classify city streets according to typologies, challenges, modal priority, and context within the built environment. At such an approach and within any context, the framework will provide relevant support strategically and locally and, therefore, allows to identify new challenges in mobility, i.e., automated vehicle design guidelines, to help inform any planned design interventions (Aukland Transport).

In Espoo, streets are classified into three main categories, as shown in figure 5: Main roads (Yellow), Major collector roads (Blue), and Local collector roads (Red). Road classification here is based on access and mobility functions of motorized vehicles but do not provide enough context about the street environment. Streets of the same classification can have different design specifications. The city designs the cross-sectional area according to different factors including, urban setting, safety, and comfort of all travel modes. (Heli,

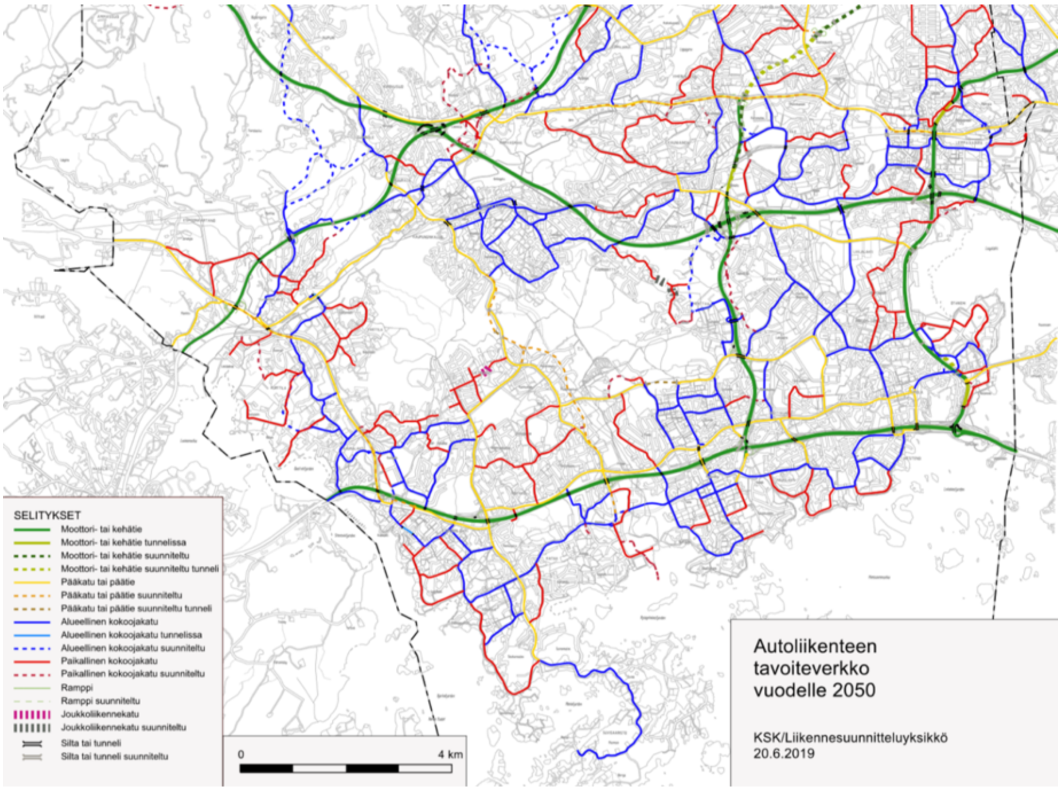


Figure 7: Espoo road network classification, (Espoo, 2019)

2019). Section 85 of the Land Use and Building Act 132/1999, mentions that streets must be designed and constructed in such a way that it adapts to its urban environment and meets requirements in functional.ity, safety, and comfort of all street users.

3.2 Street design process

The city planning department defines the needed area for the whole street with some consideration regarding the cross-sectional design and modal split. With cooperation with the city planning department, the street planning department design the detailed cross-sectional area by defining the street traffic dimensions based on three criteria: 1. Design widths of the various transport modes 2. Forecasted traffic volumes 3. The modal split. After that, other functions that need to be reserved in the street area will be identified, including, for example, escape routes, required widths of slope and edge areas, trees, etc. (Heli, 2019).

The Finnish transport infrastructure agency publishes road planning and design guidelines for designers and operators of major roads in Finland. Street cross-section and technical design are, however, produced by the city based on national design standards and guidelines. The street design produced by the city shows dimensions of the cross-section and approximate elevation in addition to all functions and structures within the street area, including median dividers, road markings, and signs, traffic lights, etc. (Heli, 2019).

3.3 Street maintenance

The technical department in the City of Espoo maintains the street and road network except for motorways, rings roads, and other public roads, which are maintained by the Finnish Transport Agency. City street maintenance include, e.g., Snow plowing, maintaining traffic signs, cleaning street areas, repairing road surfaces, etc. Winter maintenance is carried out in the order of urgency as prescribed by the maintenance classification. There are currently no minimum standards or a systematic way of maintaining the quality of line markings in Espoo. Line marking quality is currently only investigated through eyesight, and priority is given to bus lanes, intersections, pedestrian crossings, and speed limit markings (Department of road maintenance, Espoo).

4 Research methodology

With the emergence of automated vehicles in Espoo, there had been a need to discover its implications on street planning and design. This study will focus primarily on the ability for assisted driving and automated driving vehicles to understand infrastructure through camera sensors. It is still not clear whether there will be or what will be the street design requirements for AVs and how the current and future deployed automated systems will coexist with other street users in a safe and effecient street environment. Today, cities have no practical requirements that consider AVs in street design. This could be due to the statically low emergence and immaturity of the deployed self-driving technology. Street design is a complex, societal and systematic process, however due to the limitation of this thesis, the methodology will mainly investigate the implications on physical street design from the perspective of a machine vision-based (Level 2, SAE) automated system, in this case Tesla autopilot model 3 - Autopilot. However, it is important to note that physical street design cannot and should not be disentangled from other factors including societal impacts, and therefore should be discussed more holistically and systematically in planning. This can be referred to from the literature review and is going to be later discussed in the final chapter (Ch. 6).

Due to several factors, including the lack of cooperation between manufacturers, cities, and road operators, there is no clear understanding of the implications that AVs may have on street design. Until future collaborations happen, there is a need for different approaches to assessing the existing street environment. With a disrupting and fast pace technological development, it is critical to becoming aware of the ability of AVs to interact with the existing street environment at an early stage. This study will try to identify physical infrastructure and maintenance elements that may require consideration by cities and road operators in addition to opening doors for further assessment studies in the future.

The research questions are the following:

1. **How** do partially automated vehicles perform in different road environments in Espoo? **What** are their potential impacts on street design?
2. **What** are the existing street design elements that are seen to hinder the current operation of machine-vision based partially automated vehicles?
   (a) **How** do weather and light conditions affect its performance?
   (b) **How** are road operation, management and maintenance going to be affected with the introduction of automated vehicles? Including road marking maintenance.
3. **What** are other implications of AVs that should be considered when planning for future physical street design, to support the safe and sustainable emergence of automated vehicles in Espoo? **How** do short-term actions relate to longer-term planning?

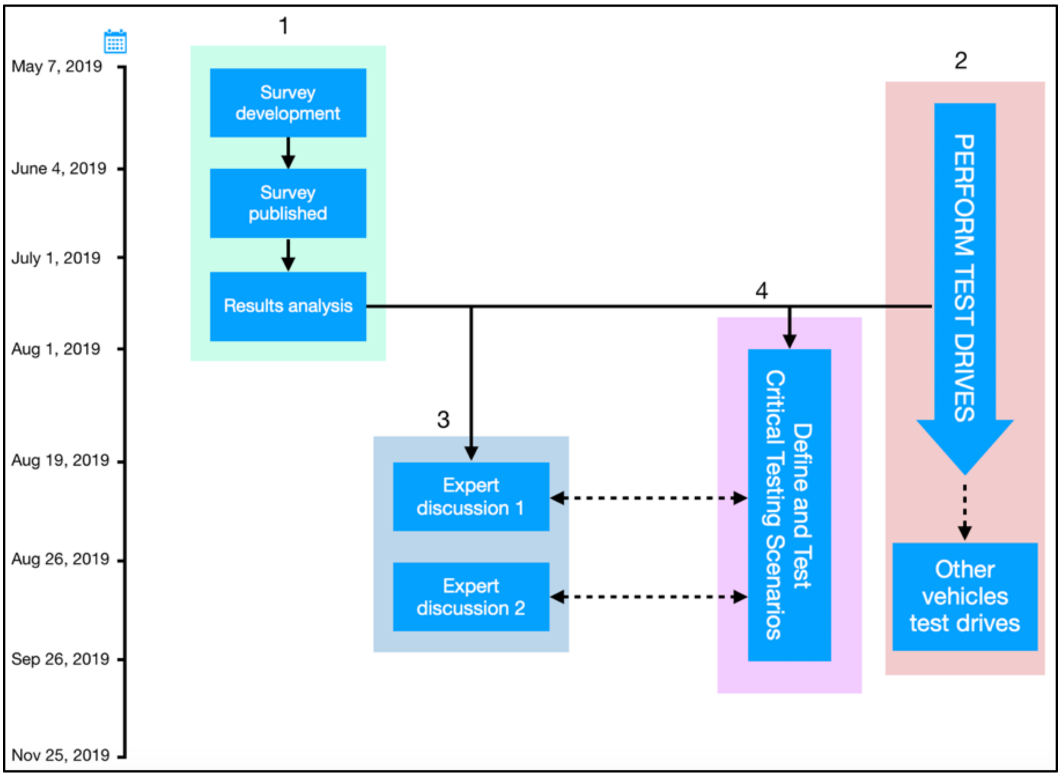


Figure 8: Research method

4.1 Research scope

The scope of the thesis covers the planning and design of the main city street hierarchy levels described in Espoo's road network map figure 7. It is important to keep in mind that in Espoo, street design can change according to its context in the built environment, ranging from rural to densely built areas. Streets in these levels of hierarchy are expected to have the highest design requirements, e.g., readability and visibility of line markings, in addition to the highest maintenance priority. However, it is important to note that in Espoo, streets at the same level of hierarchy do not necessarily mean similar cross-section design or maintenance priority.

Tesla's autopilot is arguably one of the highest commercially used advanced driving assistant system in Finland. Tesla and a few other passenger car manufacturers are using and intending to use only camera-vision, and machine learning-powered system to navigate and perceive the driving environment. Tesla's autopilot function could be turned on (in the presence of lane markings), including city streets and at intersections (even though this may not completely fall into the ODD of vehicles of this category). However, the aim of this research is to assess situations not only inside the said ODD but also situations where the system may or may not work, giving the safety of driving in these situations the highest priority.

The purpose of this study is to identify and assess key attributes in street design required by road operators to support the safe and effective operation of AVs on the road network, and achieve an optimised level of safety and mobility benefits from AVs. In addition to helping setting the ground to consider long term implications for sustainability and societal impacts.

4.2 Research methods

> "Designing streets for AVs require designers to rethink the traditional model of usage and to embrace a more data driven design process" (Austroads, 2017).

In this study, we will use triangulation to understand the phenomenon from different angles. Triangulation means using more than one method to collect data on the same topic for the study to become more meaningful. This is a way of assuring the validity of research using a variety of methods to capture the topic from different angles. However, the purpose of triangulation is not necessarily to cross-validate data but rather to capture different dimensions of the same phenomenon. Such a methodological approach will help better understand the technological ability and disability, and its implications on different aspects of street design and planning. The exploratory approach will allow a better understanding of the challenge at its preliminary stage, and to identify critical features in street design that can be the focus for future research. Figure 8 shows the framework used to assess the implications of AVs on physical street design in Espoo. In this case, we used the framework for Tesla autopilot model 3 - autopilot, Version 9.0. The framework employs four-methods, shortly described below:

1. **Survey Autopilot users:** With the help of the map-based survey tool (Mapptionnaire) and two Tesla Facebook community groups, the survey is developed and distributed online for a 25-day time span. While the collected input may provide quantitative data, it is indicative only and not statistically significant.

2. **Road test drives:** Due to its availability, Tesla Model 3 was mainly used for road test drives. In order to get familiar with the technology and its driving capabilities within different street design, traffic weather and light conditions. Test drives were conducted at different times and locations during the research timespan. All test drives have been video recorded using a go pro inside the vehicle showing the driver's street view (Including dashboard and screen), as shown in figure 10 for later desktop analysis. In addition, other ADAS equipped vehicles, including Volvo, Mercedes, Audi, and Ford, have been shortly tested in Espoo for comparison purposes.

3. **Expert discussions:** Semi-structured discussions with two Finnish experts covering the topic 'Planning for AVs and its implications on street design and infrastructure in Espoo.' Eetu-Pilli and Risto Kulmala, advisor and author of the recently published report 'The impact of automated transport on the role, operations, and costs of road operators and authorities in Finland.' Both experts have comprehensive knowledge on the advancement of the technology and its implications on transport and traffic from strategic levels. With the help of the first two methods, i.e., Survey and Real-road test drives, discussions have been steered to help identify existing street design features in Espoo that may be influenced by the emergence of AVs in the short and long term.

4. **Define and test critical scenarios:** With the help of other methods, i.e., Survey, Test drives, and Expert discussions, critical testing scenarios will be identified. Critical testing scenarios, using Tesla autopilot, will similarly be tested, and video recorded, to help analyze autopilot's behavior in certain street design conditions.

4.2.1 Road test drives

The first step of planning for an automation-ready transport network is to become aware of the capabilities and advancements of the technology (Hoadley, 2018). The sole purpose of this method is to develop an awareness of the technological capabilities and understand how a ‘machine camera vision-based automated system performs on varying street designs in Espoo and within different traffic and weather conditions.

Tesla autopilot (Model 3)

Tesla autopilot is equipped with (ADAS) features mainly consisting of lane keep assist system and adaptive cruise control ability. The LKAS function of Tesla referred to as *Autosteer* function, was the system whose performance across different test situations, is assessed. *Autosteer* feature comes combined with ACC in a package referred to as Autopilot (AP). The blue steering sign in Figure 9 informs the user that the driver assistance systems are operating. Tesla autopilot is a Level 2 automation system that uses sensors, cameras, and a linear robotic logic: sense, plan, act to navigate through the street environment. Images from its cameras and sensors are classified based on the accumulated experience of a deep neural network – an on-board supercomputer whose software is the product of extensive machine learning. The car uses “deep learning” to feed the network with big data that it can use to predict different driving tasks. Tesla’s Autopilot function can be turned on in the presence of lane markings on either side of the road, including city streets and at intersections, where it may not completely fall into the ODD of vehicles of this category. As mentioned earlier, the aim of this research is to assess situations not only inside the said ODD but also situations where the system may or may not work, giving the safety of driving in these situations the highest priority.

Figure 9: Tesla autopilot’s visual view

Driver’s manual – describing limitations and capabilities of the Tesla autopilot

The first step before performing any test drives was to go through the description of the limitations and capabilities of the Tesla (Autopilot) function in the owner’s manual. Tesla’s vehicle owner manual broadly describes the conditions under which the two associated dynamic driving functionalities: 1) Lane-keeping assistance system (LKAS) and 2) Adaptive cruise control (ACC), are designed or not-designed to operate. We will frame the described limitations [1] in the Tesla manual into the suggested ODD framework by (Traficom, 2019). The ODD framework is based on four main operational areas:

a. **Road type**

- Narrow or winding roads.
- Intended for use only on freeways and highways where access is limited by entry and exit ramps. If used on other roads, autosteer may limit the maximum allowed cruising speed.
- Lane markings: Excessively worn, have visible previous markings, have been adjusted due to road construction, are changing quickly (e.g. crossing over, merging), objects or landscape features are casting strong shadows on the lane markings, or the road surface contains pavement seams or other-contrast lines.

b. **Geographic area**

- Construction zones.
- Areas where bicyclists or pedestrians may be present.
- City streets or on roads where traffic conditions are constantly changing.

c. **Speed range**

- Minimum support speed is 30km/hr or if there is a car in front in a stopping traffic.
- Maximum speed is 150 km/hr

d. **Environmental conditions**

- Poor visibility (due to heavy rain, snow, fog, etc.)
- Bright light
- Extremely hot or cold temperatures

Data collection - video recording

For this method and the critical testing scenarios method described Figure 8, an external video recording device (i.e., Go pro) – Capable of capturing GPS data – is set up inside the car showing the driver's street view along with the dashboard and screen as shown in Figure 10.

[1] The described limitations are actual quotations from the Tesla user manual

Figure 10: Video recording setup and street view

Test drive routes and conditions

The test drives will only be done on city-operated streets, meaning that national roads (e.g., *Keha I, Keha II, and Keha III*) will not be part of our experiments. The test drive aims to test the capability of the autopilot in different road, traffic, weather, and light conditions in addition to different street context and typologies, including urban and rural streets figure 11. As mentioned in the literature review, different environmental conditions, e.g., rain, may hinder the performance of the automated system. In order to understand how different environmental conditions may alter the performance of the automated system, Tesla autopilot will be tested in rainy and night conditions.

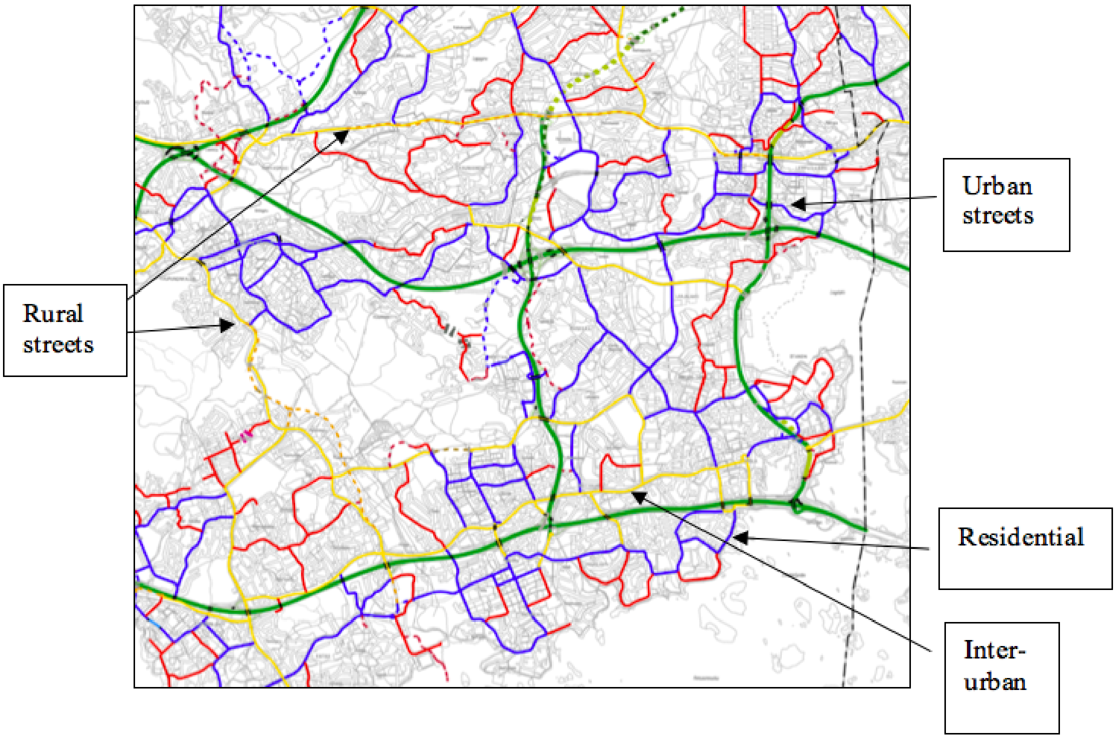


Figure 11: Street typology

Other ADAS test drives (Volvo, Ford, Mercedes, Audi)

One underlying challenge when studying the implications of AVs on street design is that automated systems, even at the same described level of automation, have varying technological abilities and therefore, different driving capabilities. To understand the magnitude of the challenge and as an extension of this method, we will test drive other ADAS vehicles, including *Volvo pilot assist*, *Ford Co-pilot*, *Mercedes* and *Audi*, which are also considered to be (Level 2, SAE) automation systems. Due to the limited availability of those vehicles, the test drives will be limited only to certain street sections and driving conditions.

4.2.2 Survey

With the help of Facebook community groups, the survey was published to allow Tesla autopilot users to map their driving experiences in Espoo using the map survey tool (maptionnaire). The survey aims to get feedback from users on how 'good' or 'bad' the automated system performs in different streets and driving conditions in Espoo. The survey questions consist of four parts, background questions, map-based experience questions, non-map-based experience questions, and demographic questions. The core questions of the survey focus on the behavior of the autopilot in different aspects of the street environment, including street design, traffic situations, weather, place, and time. While the collected input may provide quantitative data, it is important to note that it is indicative only and not statistically significant.

Map-based survey questions

The first part of the survey asks the user to locate their experiences on the map. The map-based experiences are divided into two parts, as shown in Figure 12. By aggregating the positive and negative points on the map, it will later be analyzed to help identify streets and street features that appear to be distinctive in influencing the performance of the autopilot system.

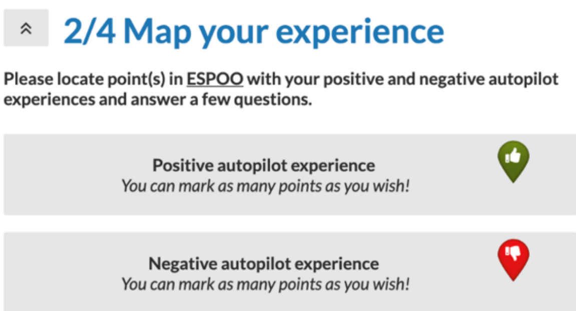
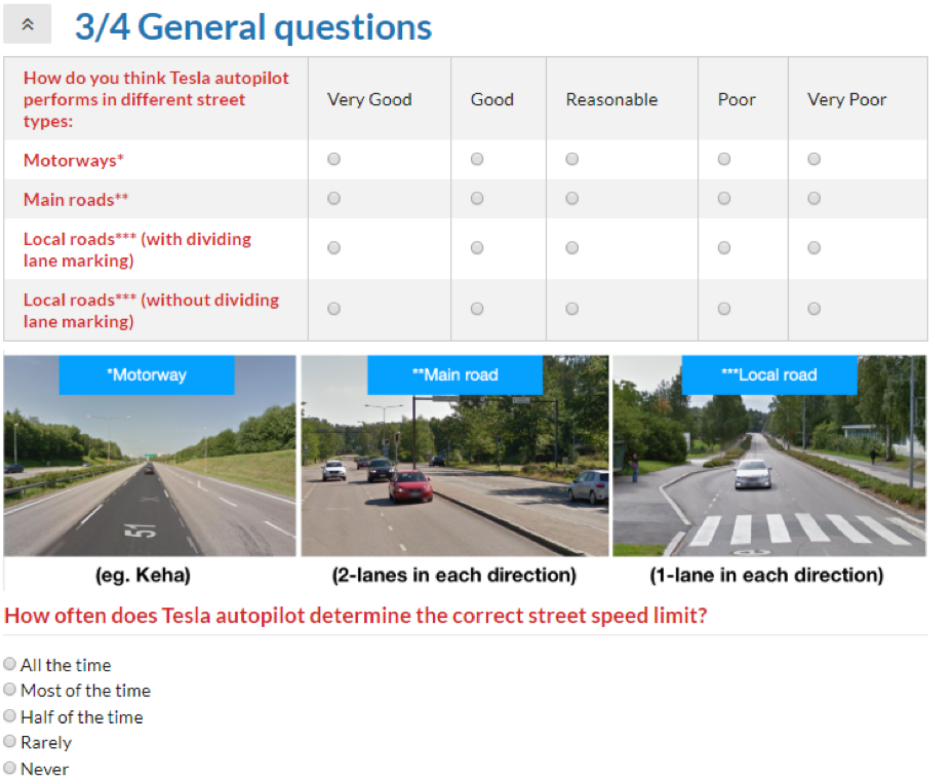


Figure 12: Survey page 2, mapping question

Non-map-based survey questions

The second part of the survey questions aims to understand how users experience autopilot in general at different levels of the road network, as shown in Figure 13. The main differentiating characteristics of the different road levels are the physical separations, lane width, number of vehicle lanes in each direction, and the design of several street elements including, line markings, bus stops, road medians, and intersections.



3/4 General questions

How do you think Tesla autopilot performs in different street types:	Very Good	Good	Reasonable	Poor	Very Poor
Motorways*	○	○	○	○	○
Main roads**	○	○	○	○	○
Local roads*** (with dividing lane marking)	○	○	○	○	○
Local roads*** (without dividing lane marking)	○	○	○	○	○

*Motorway (eg. Keha)
**Main road (2-lanes in each direction)
***Local road (1-lane in each direction)

How often does Tesla autopilot determine the correct street speed limit?

○ All the time
○ Most of the time
○ Half of the time
○ Rarely
○ Never

Figure 13: Survey page 3, general questions

4.2.3 Critical testing scenarios

To narrow down the scope and to investigate critical street design features, we will use several data inputs, including Survey results, Test drive experience, and Expert discussions to define and conduct critical test drive scenarios, as shown in Figure 14. Street design elements, features, and locations for the critical testing scenarios are shown in Table 1. The last method will help identify several scenarios for assessing the operation of Tesla's Autopilot. Those are mainly related to features of longitudinal road markings, including design and quality.

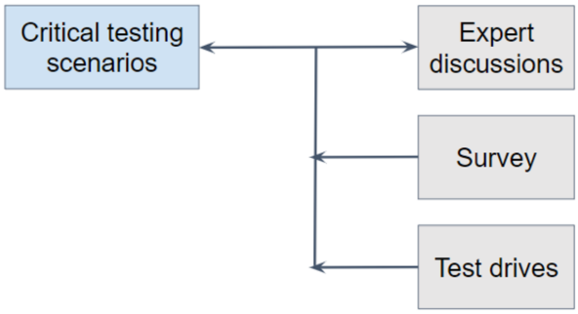
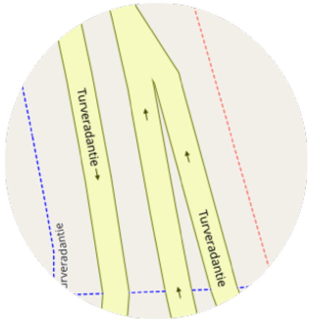


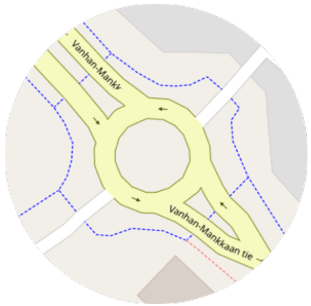
Figure 14: Defining critical testing scenarios

Table 1: Critical testing scenarios

Street design element	Feature	Location	Comment
Road Geometry	Horizontal curve		The Horizontal curve prior to the intersection may hinder the sight distance of the machine vision.
Road marking	Lane split		Lane split prior to an intersection with both white and yellow colored road markings.

Lane merge		City lane merges after exiting the roundabout. Two-testing scenarios: with and without edge line-marking paint.
Low quality road marking		Low-quality center line marking paint, due to road works.

	Intersection road marking		Uncommon T-intersection edge line marking design.
Other Design Elements	Side parking		Side parking bay without edge marking.

Road Medians		Several road medians are situated in Sinimäentie, acting as a traffic calming design element and used for pedestrian crossings.
Roundabout		Single-lane-city -roundabout, without edge lane markings.

4.2.4 Expert discussions

Semi-structured discussions with Eetu Pilli-Sihvola-Sihvola, *Chief advisor of Connected and Automated driving at Traficom (Finnish Transport and Communications Agency)*, and Risto Kulmala, *Senior advisor of transport telematics and autonomous transport at Traficon (Transport planning consultant)*. Eetu-Pilli and Risto Kulmala, *advisor and author of the recently published report 'The impact of automated transport on the role, operations and costs of road operators and authorities in Finland'* have comprehensive knowledge on the advancement of the technology and its implications on cities, streets, and traffic on a national and international level. With input from the Survey and road test drives, discussions have been steered to help identify features in street design in Espoo that may be influenced by the emergence of AVs in the short-, medium- and long-term. The dialogue was structured to support the research questions and to allow an understanding of strategic-national level planning and actions towards AVs and street design, as shown in Figure 15.

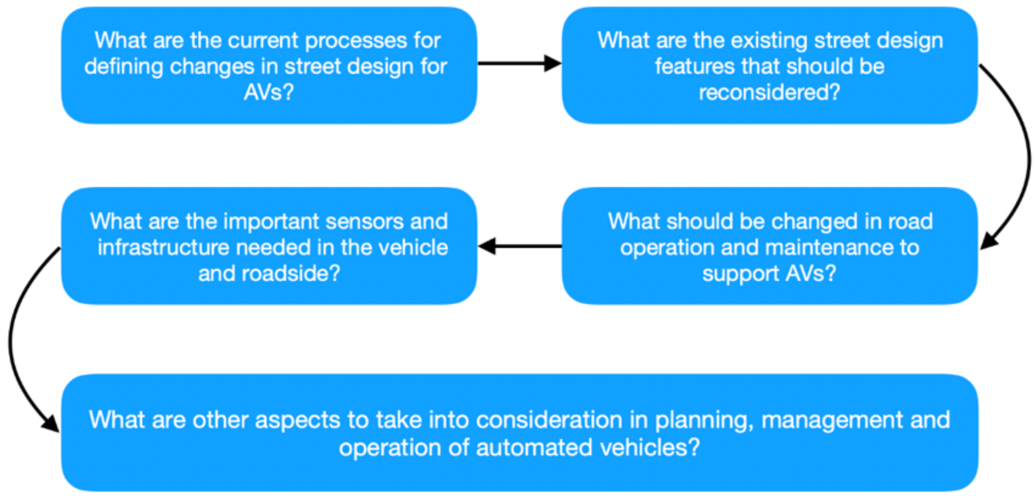


Figure 15: Framework of the semi-structured expert discussions

5 Findings

In this chapter, findings from the research process are presented in four sections, representing outcomes from each of the four methodologies explained in figure 8. With this framework, the purpose is to approach the phenomena from different angles in an attempt to understand the implications of AVs on street design in Espoo.

5.1 Survey

In this section, findings from the survey responses are presented. The survey was published three times on two Facebook groups i.e., Tesla Model 3 Owners Club Finland and Tesla Club Finland, with 1500 and 3,500 group members, on a span of 25 days in May 2019. The online survey had 47 responses, 37 after cleaning. Most of the users used the autopilot feature almost every day. 45% of the respondents have been using autopilot only in the past three months from the date of the survey. Most of the users have gotten familiar with using the autopilot either by experimenting or from online sources, while only a few people stated that they used the owner's manual — Appendix A.

Non-map-based survey results

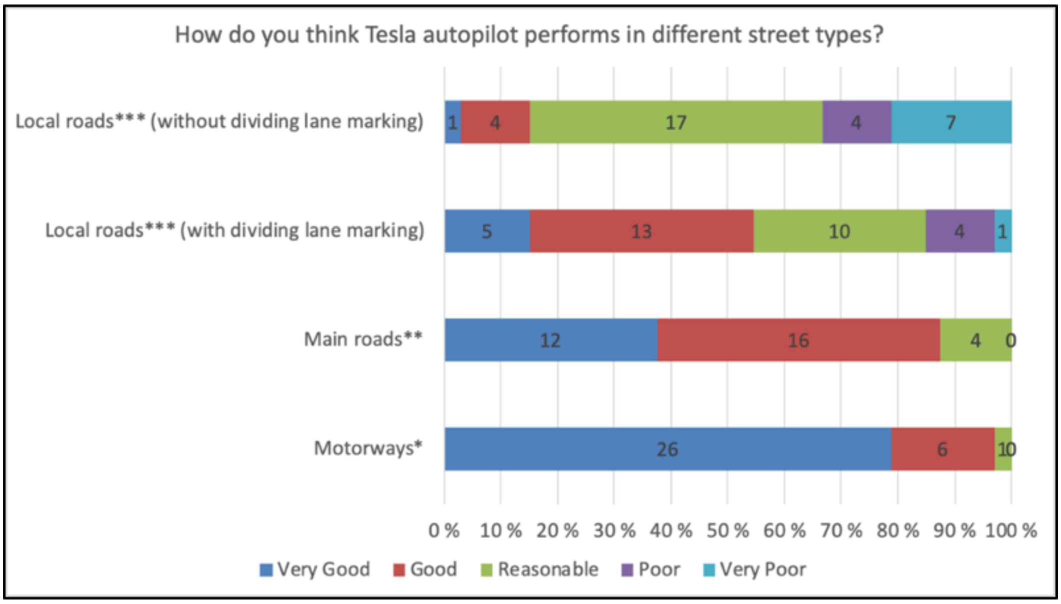


Figure 16: Survey results, Autopilot performance in different street types

According to figure 16, Tesla autopilot users, in general, had positive driving experience using autopilot on roads with lane markings in Espoo. On the other hand, most people had either reasonable or negative experiences using autopilot in roads without diving lane markings. 50% of the respondents stated that while using autopilot, the system determines the correct street speed most of the time. Only a few people said that it rarely or never gets the correct speed limit. Detailed results are shown in Appendix A.

Figure 17 shows the map responses, Red representing negative experiences, and Violet representing positive experiences. Table 3 summarizes the described positive experiences with information about traffic light and weather conditions in addition to the road location and type according to users' responses. Table 5 summarizes the negative experiences according to seven negative autopilot driving scenarios, also showing detailed information about the traffic, light, and weather conditions in addition to the road type, location, and geometry.

Map-based survey results

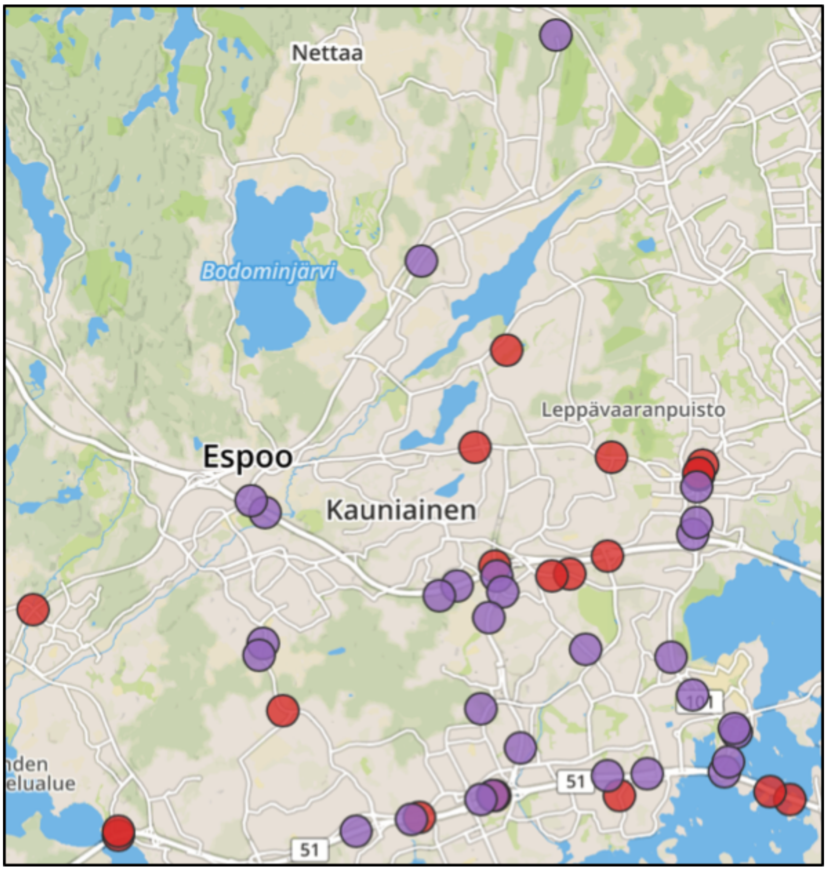


Figure 17: Map responses, maptionnaire, red shows negative experiences, blue shows positive experiences

Table 3: Summary of positive map experiences

Positive experience	**Number of respondents**	**Road type**	**Weather, light and traffic**
Highway and Interchange	20	Highways: *Turunväylä, Keha I, Keha III, Länsiväylä*	All conditions except (snowy, foggy, only car lights)
Small tunnels	2	Main Roads: *Säterinkatu, Hevosenkenkä*	Rainy, Car and street lights, empty road & Clear, sunlight, normal.
Curves	3	Main Road: *Finnontie* & Local collector road: *Kruununtie*	Clear, sunlight, normal.
Round-about	1	Main Collector road: *Vanhan-Mannkaan tie*	Clear, sunlight, slow traffic.
Rural road	1	Single lane (two-way) rural road divided with lane marking only: *Nipperintie*	Clear, sunlight, slow traffic.

Table 5: Negative map experiences

Negative experience	**Number of respondents**	**Road type**	**Weather, light and traffic**
AP drifted to curb or road median	8	Highway: *Länsiväylä*, Main collector road curve: *Westendintie*, Main Road: *Finnoontie*, Main collector road, lane narrows at crossings: *Sinimäentie*, Highway: *Keha I*	*Clear, car lights, Normal traffic. - Clear, sunlight, Empty road. - Clear, sunlight, Normal traffic. - Clear, sunlight, Normal traffic. - Clear, sunlight, street and car light, normal and empty traffic.*
AP drifted towards a different lane or another vehicle	5	Highway: *Keha II*, Main collector road: *Sinimäentie*, Main road: *Turuntie*	*Clear, sunlight, Empty road for all roads.*
AP stopped unexpectedly due to vehicles (NOT) on the same lane	3	Highway: *Länsiväylä* & Highway tunnel: *Keha I*	*Rainy, sunlight, normal traffic - Clear, sunlight, normal traffic.*
AP failed in a Construction work area	2	Highways: *Länsiväylä, Turunväylä*	*Clear, sunlight, normal traffic.*
AP failed to recognize lane ending	1	Local road: *Laaksolahdentie*	*Clear, sunlight, empty traffic.*
AP waves from side to side when entering the intersection	2	Intersection: *Länsiväylä from Keha II*	*Clear, sunlight, normal traffic.*
AP failed to overtake a (stopped) vehicle in a wide lane.	1	Main road: *Turuntie*	*Clear, sunlight, normal traffic.*

5.2 Test drives

In this section, findings from the conducted test drives of Tesla Autopilot and other driver assistant systems are shown. Appendix B shows the routes where Tesla Autopilot was tested in Espoo in addition to routes of other test drives, which took place in different weather and light conditions. Most of the findings with regard to street design and traffic is related to the performance of the steering assist feature, which Tesla calls *Autosteer*. In the text, findings will be supported by screenshots incorporated from the recorded videos along with explanations of the system's behavior.

Unlike highways, city streets have more design fluctuations due to continually varying traffic, spatial, and geographical patterns. From the analysis of the test drives, shown in detail in Appendix B, it becomes apparent that Autopilot performs better on some roads than others. Autopilot, in general, operates better in more controlled street environments with consistent design in the number of lanes, lane width, and road markings in addition to roads with minimal curvature. In general, Autopilot performs better on roads with high-quality road markings than others. However, Autopilot's machine vision can most of the time recognize curbs and other surfaces when driving through a changing street design environment. This can be noticed, for example, in rural roads e.g., *Finnontie*. Similar observations are observed during rainy and night test drives. Overall, it seems that mild rain or night driving does not have any significant changes on the behavior of the Autopilot, compared to driving in a clear light day.

Today, Autopilot's machine vision does not fully recognize or effectively react to all physical design elements, which sometimes results in an unsafe or uncomfortable driving behavior. Unrecognized street design elements, including crosswalks, intersections, speed bumps, steep horizontal curves. In addition to other temporary street elements, including roadwork elements, traffic cones, and other features that may appear during driving, including animals. However, according to Tesla's owner manual, Autopilot's machine vision and system fusion are not yet designed to operate on streets with such elements.

Below are general findings from the conducted test drives in Espoo: (Findings are based on trends in the driving behaviour of Tesla Autopilot)

1. **Lines, the clearer, the better.** In Espoo, the quality of road markings can vary from a place to another and within a specific road. Autopilot can currently recognize low-quality center and edge lane markings and curbs; however, in other situations, such as bus stop markings, it may cause uncomfortable and slow reaction time.

2. **Yellow markings sometimes confuse Tesla's machine vision.** In Espoo, yellow paint is sometimes used along with white markings, for example, to separate opposite traffic or at lane splits, e.g., *Sinimäentie*. In situations where there is a constancy in line marking color, yellow or white, line markings are reasonably well-read. However, in areas where white marking appears along with yellow lane marking, it may confuse autopilot's steering assist into driving in the wrong direction. In such cases, it has to also be noted that the yellow markings are continuous, unlike the dashed white markings. It seems that Autopilot prioritizes continuous yellow markings more than dashed white markings.

3. **Wide lanes can sometimes confuse Tesla's machine vision.** In locations where the lane's edge is not defined by either a line marking, curb, change in surface material, or color, Autopilot does not seem to recognize the lane extent and therefore considers, for example, a lane with unmarked side parking as a wide lane. Overall, it seems that autosteer performs better in narrower, more defined lane layout design.

4. **Special line marking designs may confuse machine vision.** Distinctive road markings design including lane split, lane merge, bus lane markings, and intersection marking design can sometimes confuse machine vision and lane detection into taking the wrong direction, which can result in unsafe driving condition.

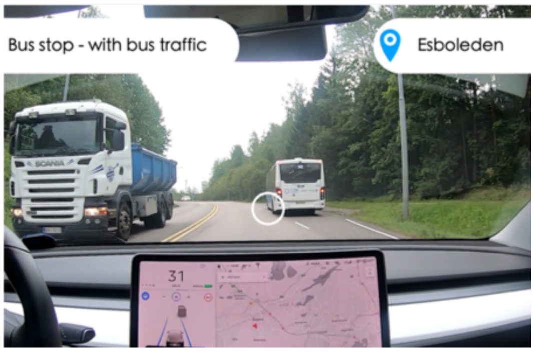


Figure 18: Autopilot lane marking detection hindered by bus-tire

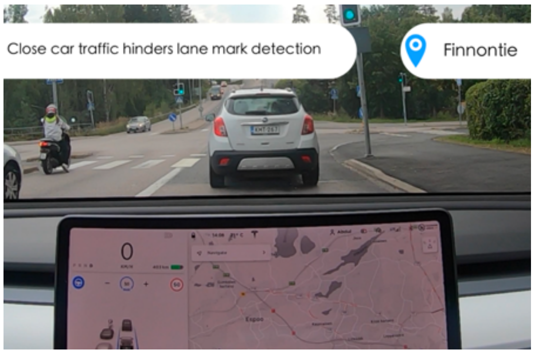


Figure 19: Car hinders autopilot lane detection 1/2

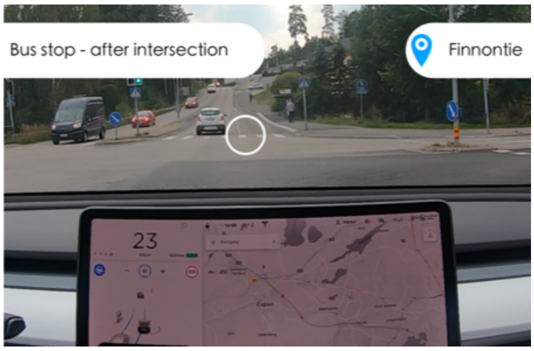


Figure 20: Car hinders autopilot lane detection 2/2

Figure 21: Same location as in figure 19 with no traffic in sight

5. **Other vehicles on the road may obstruct the view of machine vision and hinder its ability for lane detection.** It has been observed from the test drives that the performance of the autopilot can be affected by surrounding vehicular traffic, due to, for example, obstruction of the machine vision's sight distance and lane marking detection. Shown in figure 11, the bus tire on the lane's right side seems to hinder the autopilot's lane marking detection, which causes the autopilot to unreasonably stop in traffic, unable to overtake the bus. Figures 12, 13 show a scenario where close car traffic obstructed the view of the system and therefore caused a slower reaction for autopilot's lane detection. However, in the same location, as autopilot travels with a traffic-free sight, as shown in figure 15, lane detection becomes smoother and faster.

5.2.1 Other ADAS test drives

As an extension to this section, we will present findings from test drives of other ADAS-steering assist equipped vehicles of other vehicle manufacturers, including Volvo, Ford, Mercedes, and Audi. Due to the limitation and availability of the vehicles, testing will only cover smaller road sections and within limited driving conditions. However, the aim of this section is only to give an indication and provide a brief comparison between the capabilities of the different ADAS systems within similar driving conditions. Figures 22, 23, 24, 25 show the visual appearance of each of the systems as it appears on the dashboard. All the steering assist systems use green color, as shown in the figures, to indicate that the steering assistance feature is on. All systems are allowed to operate in places where they may not be designed to be used, which causes it to sometimes operate erratically in these situations rather than locking the system out. Below are general observations from the test drives:

1. **In all systems, steering assistance, can toggle between off and on at any time.** Sometimes without any sound or visual warning. All steering assistance systems had trouble with curvy roads and frequent lane departures. However, some systems were better than others. Overall, all steering assist systems were far less capable of driving in city roads than Tesla's autopilot.

Figure 22: Volvo ADAS

Figure 23: Ford ADAS

Figure 24: Mercedes ADAS

Figure 25: Audi ADAS

2. **Good quality lane markings are significant for all the ADAS systems.** Most systems had difficulty navigating the road in cases where lane markings are not consistent or when other road surfaces appear on either side of the road, including curbs and road medians. One of the areas explored in the test drives was how important edge lines were to the successful detection of the road edge, or how well the systems could work out the edge of the road in the absence of edge lines. Responses indicated

that only some systems could detect concrete kerbs and shoulder edges, and with less confidence than for marked lines. In most cases, an edge line was considered important.

3. **All ADASs were not able to drive through road medians.** Due to the steep curves around some road medians in Espoo e.g., Sinimäentie, steering assist systems were not able to operate effectively. The driver had to disengage to manual mode in most situations. Moreover, none of the systems provided ample warning to the driver as it approaches a difficult driving situation, which causes it to operate in places where it's not designed to and thus causing unsafe driving.

4. **Some of the systems do not reliably recognize stopped vehicles in traffic** when operating with adaptive cruise control feature, which either causes sudden and uncomfortable stops or requires the driver to disengage into manual driving mode.

5.3 Expert discussions

In this section, we will present Finnish expert views and anticipations on the development of Self-driving technology and its implications on cities, street design, and road infrastructure in Finland. As shown in figure 15, the discussions were guided by several questions to cover different aspects of the topic. Findings from the discussions will be presented accordingly. Discussions were mainly framed around short and long-term implications on different aspects of transport planning and traffic management, mainly focusing on street design, road maintenance, and operation. Both experts argued that the implications on street design and infrastructure will highly depend on the developments and capabilities of the technology and the deployed use cases.

Today, on a national and regional scale, there has not yet been any long-term planning for automated vehicles. This, according to the discussions, is thought to be mainly due to the high uncertainty of the technological development and use case deployment in the city. Automation technology is constantly going through changes, therefore, requirements for road operators that may be applicable today, can become trivial in the future. Similarly, requirements in street design and operation will highly depend on the use cases of the deployed AVs.

> Eetu Pilli-Sihvola: if just shuttles at low speeds then of course it's kind of different the requirements are not that kind of big and then passenger cars on one hand. . .

Implications of automated vehicles are only expected to become visible when the responsibility of the driving task transfers partially or fully from humans to the machine. On the other hand, ADAS equipped vehicles are only meant to assist the driving task in certain driving conditions. Consequently, Eetu Pilli-Sihvola suggests that cities should constantly be knowledgeable on the development of the technology, in order to avoid making decisions in street design that may hinder the operation of AVs in the future.

> Eetu Pilli-Sihvola: ...for example left turns in urban environment are extremely extremely difficult for any automated vehicles right now. I mean short term if you want to look at how to plan routes for automated vehicles or maybe guide them through the city you would go as far right turn only, kind of best practice from the logistics field... wide crossings is also a problem for the current technology...For example, roundabouts are seen to work better than regular 4-leg intersections due to lower number of conflict points.

Today, road markings appear to be the key attribute for the operation of automated vehicles in the short-term. Cities should therefore consider the design and maintenance of lane markings if AVs continue to rely on camera systems for lane marking detection. This may to also impact road maintenance and operation, to allow better quality and visibility of markings. The maintenance aspect should also be discussed within specific driving conditions, including snow and ice, as they are common in Finland. However, due to its high expenses, winter maintenance may only become a viable option in high volume traffic environments, e.g. highways. One of the seen challenges in road marking design today, is the design of temporary road elements. This is expected to become more crucial as automated vehicles become more common. Eetu Pilli-Sihvola suggested considering several road marking design features that may impact the operation of ADAS systems today, including lane narrowing and widening, lane merge and lane splits, bus stops. Moreover, he also suggested investigating environmental impacts on machine vision, including sun light exposure and snowy conditions.

> Risto Kulmala: In the short term It's mostly the temporary road design features like road work... today they are the ones that the automated vehicles cannot cope with really because there is no standardized way of marking them...

Other street design features are anticipated to become more relevant in the longer term. This is expected to be influenced by various factors including technical digital infrastructure and vehicle connectivity, Operation design domain of AVs and geofencing restrictions in the city. In addition, this also be relevant to the deployed use cases and automation capability.

> Risto Kulmala:...we should have all the traffic management information be digitally available, so that automated vehicles should know what rules and regulations apply to a certain place what are the properties of this connection and how they are related to their routes and destinations...

Road operators are suggested to think of the road network as an asset for multiple users in future planning, management and operation of AVs. Further investigations in street design may require more studies on the interaction of AVs with pedestrians and cyclists. The separation of road users is one crucial aspect to be considered when planning future streets. It is however important to think of the transport system as a whole when considering any innovative changes in street design in the future.

Eetu Pilli-Sihvola: Often there is also the discussion whether there should be kind of separate lanes for automated vehicles. . . it's hard to kind of recommend that as a best practice for any city if you try to look kind of at the big picture at the same time. . .

Risto Kulmala: I think the concept of separation of road users has to be rethought so where you want to have those common space. . . some vehicle manufacturers are not happy to have bicyclists in the same road way, that would mean that with all those nice plans where they are talking about the common space it would not work perfectly well with such automated vehicles...

5.4 Critical testing scenarios

Today, AVs are using cameras to perceive the road environment through the recognition of several street design elements. In this section, observations from critical scenario test drives of Tesla Autopilot will be shown below, to allow an understanding of the performance of machine vision based AV with the existing street design and infrastructure.

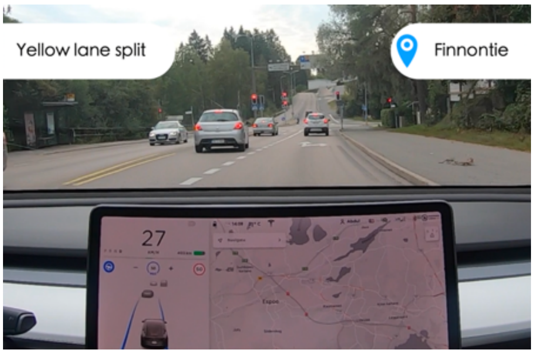


Figure 26: Yellow lane split marking, Finnontie

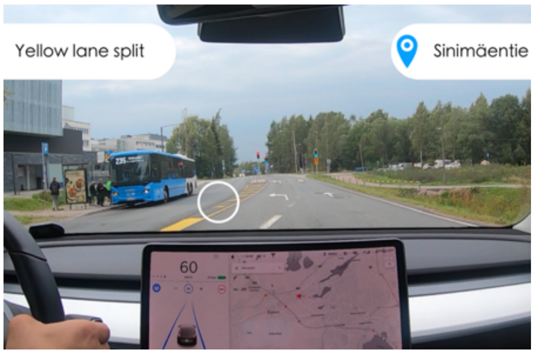


Figure 27: Yellow lane split marking, Sinimäentie

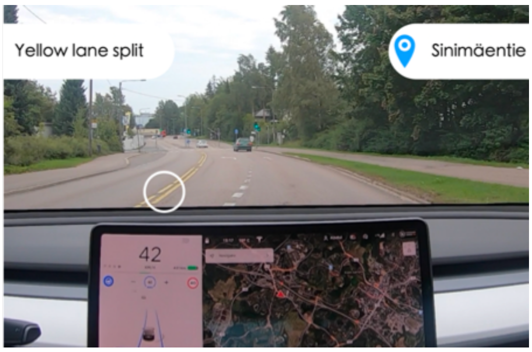


Figure 28: Yellow lane split marking, Sinimäentie

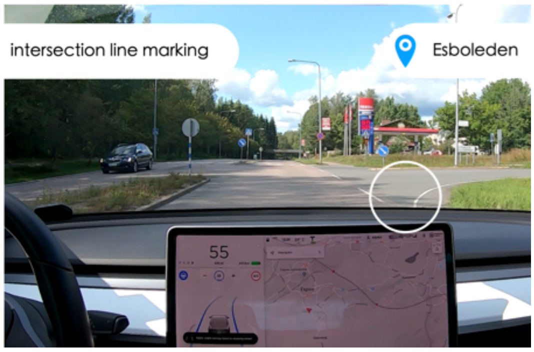


Figure 29: T-intersection line marking design, Esbonleden

Yellow line-markings at lane splits sometimes confuse Autopilot. In Espoo, yellow line-markings, as shown in figure 26 are sometimes used to separate the traffic. In general, it has been noticed that yellow or white paint caused no issues for lane marking detection for machine vision when either of the colors is used at once. However, in the case where yellow line marking is shown amidst white paint or vice versa, as Autopilot approaches the lane split, line marking detection is confused on which lane to take. In this case, the vehicle travels to the left lane following the yellow marking.

Intersection marking design can confuse Autopilot's driving direction. In this case, as shown in figure 29 in the car's screen with blue lane markings showing the vehicle's traveling direction, the curved line marking going to the right direction at the T- intersection confused the Autopilot into taking the right exit instead of continuing in a straight direction.

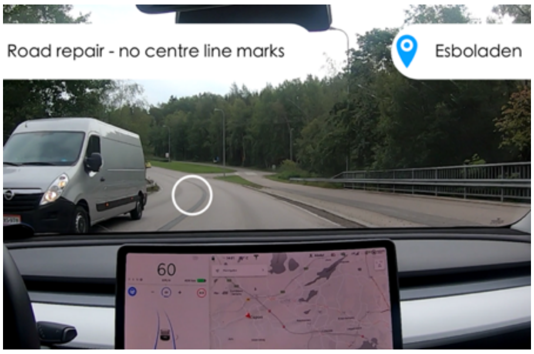


Figure 30: Low quality line marking - road repair, Esboladen

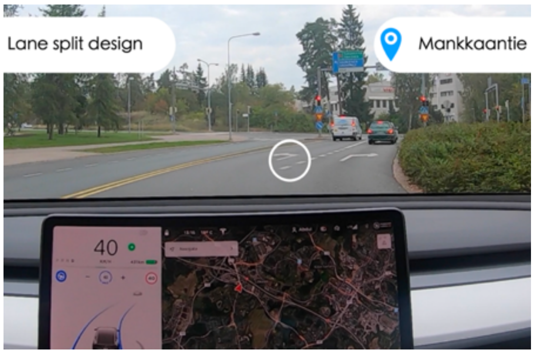


Figure 31: Unusual lane split marking design, Mankkaantie

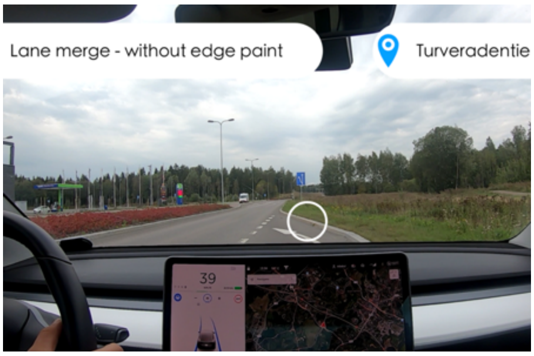


Figure 32: Lane merge design, without edge paint Turveradentie

Figure 33: Lane merge design, with edge paint, Turveradentie

Low-quality line markings are not that confusing for Autopilot. In Espoo, center and edge markings are not always visible on all roads due to cases like road repair works. Figure 30 shows an example of this case. In this case, no white center line-markings are visible along this road section. On this road, Autopilot had no issues detecting the lane.

Some lane split marking designs may confuse autopilot lane detection. Unlike most lane split designs in Espoo, lane split marking, which in this case appears after a horizontal curve as shown in figure 31, is not connected to the lane separator marked with yellow. This caused Autopilot to disengage as the car traveled on the white lane marking separating the left and right turns.

Autopilot does not operate effectively at lane merges. Due to the limited space in city streets, lane merge design is not as wide or gradually curved as in highways, as shown in figure 32 and 33. As a result, Tesla autopilot does not react adequately to sudden changes in the lane direction. This scenario had been tested in two cases, with and without edge control paint. In both cases, the autopilot recognizes the curb and lane change but does not react effectively.

Autopilot can operate through road medians. Road medians are present in many roads in Espoo, including main roads with 50 km/hr speed limits, acting as non-signalized traffic calming tool and a pedestrian crossing. Autopilot recognized road medians on the road and avoided hitting the curbs successfully. However, the system does not slow down in such situations and instead travels at the speed limit, which sometimes results in an uncomfortable and unsafe driving situation. In similar situations, Autopilot does not detect or slowdown for other geometric or road surface traffic calming elements, including lane narrowing, bumps, and horizontal curves.

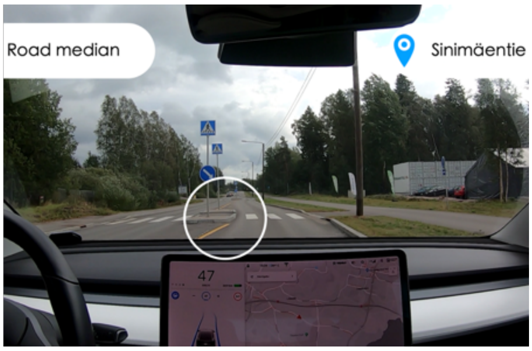


Figure 34: Road median/island, Sinimäentie

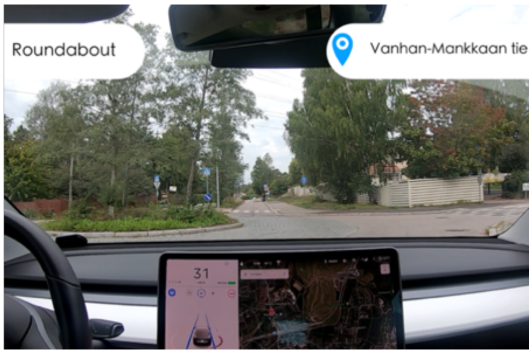


Figure 35: Roundabout, Vanhan-Mankkaan tie

Figure 36: Side parking with no edge line marking, Tekkarikylä

Autopilot does not recognize or operate in roundabouts. Roundabouts are usually found in many local roads in Espoo, as shown in figure 35. Some of the roundabouts, especially the ones that have single lanes, have no line-markings to guide vehicles. At this stage, Tesla autopilot does not recognize the roundabout and tries to go in a straight direction.

Autopilot confuses side parked vehicles as stopped traffic. In Espoo, on-street parking is permitted on some roads, as shown in figure 36; however, parking bays are not always marked. In this case, Tesla autopilot mistakes vehicles parked on the side as stopped traffic and therefore stops unexpectedly.

Autopilot does not operate safely on curves without control markings. Some roads in Espoo are not marked to guide and separate traffic, as shown in figure 30. Autopilot, most of the time, detects the lane's direction even without lane markings when going in a straight direction. However, in this case, the road is curved and separated by a median without line markings on either side. Autopilot detects the curve but does not react safely and therefore tries to hit the median curb. On the other hand, autopilot works better in a curved median intersection that has guiding control markings on one side of the lane, as shown in figure 31.

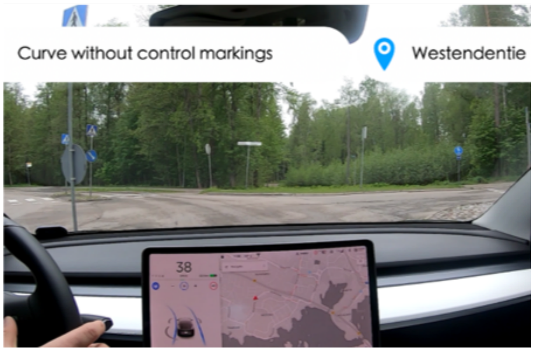


Figure 37: Curved road median intersection, Westendentie

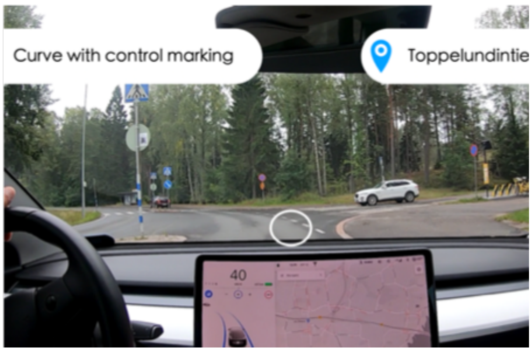


Figure 38: Control markings along intersection, Toppelundintie

6 Discussion

The findings of this study indicate several elements in Espoo's street design that may require future considerations in design, maintenance and implementation. The study utilized a combination of qualitative methodologies to study the implications of machine-vision based automated systems on Espoo's traffic and street design environment. Consequently, the findings illuminate the topic from various angles. Overall, the framework allowed two supplementary approaches to be utilized in this study. First, through the survey, test drives, and expert discussions, it allowed the identification of physical street design elements and driving conditions that are seen significant for the operation of AVs. On the other hand, through critical testing scenarios, it enabled further exploration of how physical infrastructure and maintenance elements may or may not influence the behaviour of Tesla's steering assist system 'Autosteer'. The primary findings from road testing allowed more detailed observations on the behavior of Autopilot with several road marking design elements. It was observed that elements, including yellow road markings, intersection line marking, lane split and merge, and other physical street elements, such as road medians and curbs, challenged the operation of driver assistance systems at varying degrees.

The views of the two traffic and transport professionals indicated several uncertainties and concerns regarding the emergence of AVs on municipal roads. There are currently no concrete recommendations for Finnish cities on how to prepare for AVs, and both interviewees anticipate that future infrastructure implications will mainly depend on different scenarios of technological development and deployed use cases in the city. Overall, the discussions touched on several themes concerning road operation and management, including vehicle connectivity and roadside infrastructure, road maintenance, vehicles operating design domains and use cases, physical and digital street design and considerations of other street users within the design and planning process. At this stage, the interviewees suggested that cities should start by developing an awareness of the technology, to avoid making decisions that may hinder AVs' performance in the future. In the context of transport planning, cities should consider AVs in a holistic manner, to avert making changes that would negatively impact other street users. Potential requirements for the deployment of AVs on planning include studying their interactions with bicycles and other road users. The interviewees also exhibited concerns about the challenges of the Finnish weather, where snow is expected to hinder the performance of machine vision-based automated systems and roads may, therefore, require active maintenance if AVs continue to operate with this technology. However, based on some preliminary studies mentioned in (Traficom, 2019), this will induce high costs for road operators and perhaps will not be a viable option for cities. In the future, roadside infrastructure, along with connected vehicles, may help support different tasks, including positioning, and thus avert the need for active winter maintenance. However, such infrastructure will result in high operating and maintenance costs. Nevertheless, such changes in infrastructure are not expected in the near future.

Based on the survey results, it is apparent that current users of Tesla Autopilot are already using the steering assist system on Espoo's road network, mostly on main roads, including rural and city routes, but also in some cases, on local streets, contrary to the recommendations in the user manual. Overall, the results indicate that the performance of the Autopilot becomes increasingly limited at the lower levels of Espoo's hierarchical road network.

Based on users' mapped experiences, this, in most cases, is due to road marking design and quality. Moreover, based on the test drives, it was observed that in addition to road markings, physical and geometric design features, including road curvature, lane widening and narrowing, curbs, and road medians, may challenge the operation of AVs. Besides street design, it was observed that some traffic scenarios could alter the behaviour of the automated system, including failure to overtake stopped traffic in cases where the machine vision's sight and lane marking detection is obstructed by other vehicles. Tesla autopilot test drives, along other driver assistant systems, also revealed another side of the challenge for road operators concerning the implications of the emergence of AVs with different automation capabilities. It is important to note that the findings concerning the implications on road design are mostly based on the behaviour of Tesla Autopilot's steering assist system, and other ADAS systems, may not have the same capabilities or requirements towards street design. For example, based on other ADAS test drives, responses indicated that only some systems could detect concrete kerbs and shoulder edges, and with less confidence than for edge line markings. In most cases, an edge line was considered important.

Such street design elements do not pertain to a single road classification; on the contrary, they exist in most municipal roads in Espoo. Unlike the road classification map in Espoo, street design seems to change more drastically between urban and rural roads, due to several factors, including urban form, types of existing street users, and modal priority. With the current advancements of the vehicle technology, it was observed that not all street design and marking elements can be assessed by Tesla's machine vision. Below is a table for assessable and not assessable street design features.

Assessable	Not assessable
Longitudinal road marking features: • Colour: *white*, *yellow* • Type: *lane split*, *lane merge*, *edge marking* • Quality: *low quality centre or edge markings*	Transverse road marking features: • *Crossing, other intersection markings*
Other design elements: *curbs, medians, horizontal curves*	Other design elements: *Speed bumps, vertical curves, speed limit signs*

Summary of road marking design findings[2]

It was identified that for assisted driving systems, the key infrastructure attribute is the longitudinal road marking design. Different line marking characteristics, including types, quality and curvature, are seen to affect the operation of the steering assist system. From the

[2] Findings are based on observations from road drives in Espoo using Tesla Model 3 Autopilot, Version 9.0.

test drives, it is generally observed that both, road marking design and quality characteristics are relevant for the interpretation of infrastructure by the machine vision systems on AVs. This section will provide drawings to illustrate our findings.

Edge marking

In road sections where side curbs exist along the road instead of conventional edge markings e.g. Merituurentie and Mankaantie, Autopilot's steering assist system, in most cases, could recognize them for positioning and lane centering. This has also been clearly noticed from the lane merge testing scenario, where the behaviour of the steering assist system had been tested several times in the presence and absence of edge markings. It was observed that the performance of the steering assist system at lane merges, does not depend on the presence or lack of edge markings within the lane merge; however, it appears that the Autopilot recognizes the lane change from the side curb but does not react accordingly, in this case, due to the sharpness of the lane change design as shown in figure 32. From the test drives, it was generally observed that edge markings are most important in road sections with no side curbs, e.g. at intersections and curved road sections, and their presence provides a clear benefit for the steering system as illustrated in Figure 39. Nevertheless, edge markings are not visible in all intersections in Espoo, as demonstrated earlier in figure 37.

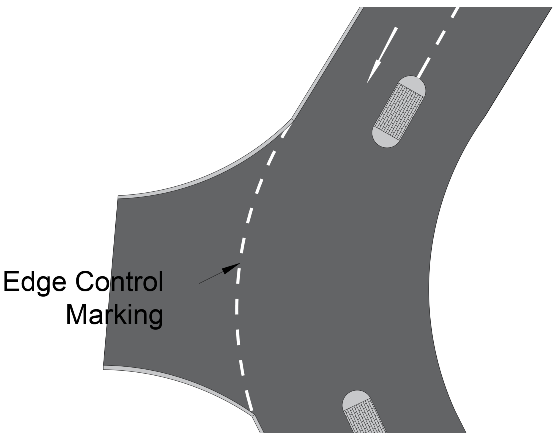


Figure 39: Edge control marking

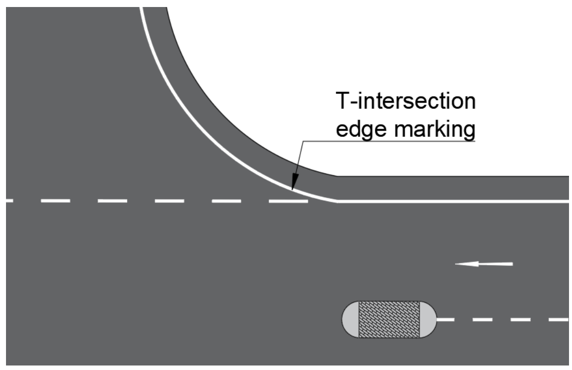


Figure 40: Edge marking at T-intersection design

However, there has been one case where the intersection edge marking design caused lane departure, and resulted in an unsafe deviation in driving as demonstrated earlier in figure 29. Figure 40 shows the design of the lane marking at the T-intersection where it had several times confused Tesla's machine vision into driving into the wrong direction. It was observed that the continuous edge marking at the intersection may have confused Autopilot into following the right exit.

Lane marking color

In Espoo, both white and yellow colours are used for road markings. In some cases, yellow markings are used to separate traffic in rural roads in, e.g. Finnontie and Turuntie. In almost all test drives, machine vision identified the continuous yellow center lane markings for lane positioning and centering. However, in other cases where continuous double yellow line markings are used in some lane split designs in Espoo as shown in figure 39, it had consistently caused lane departure for the steering assist system, and confused the Autopilot system into deviating to the left direction, rather than continuing in a straight direction. Similar to the previous case of T-intersection continuous edge marking design, it is observed that generally, machine vision detection prioritizes continuous markings for lane centering than dashed markings.

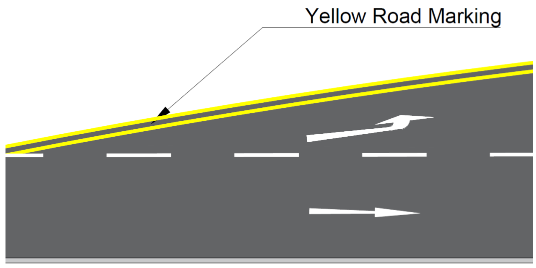
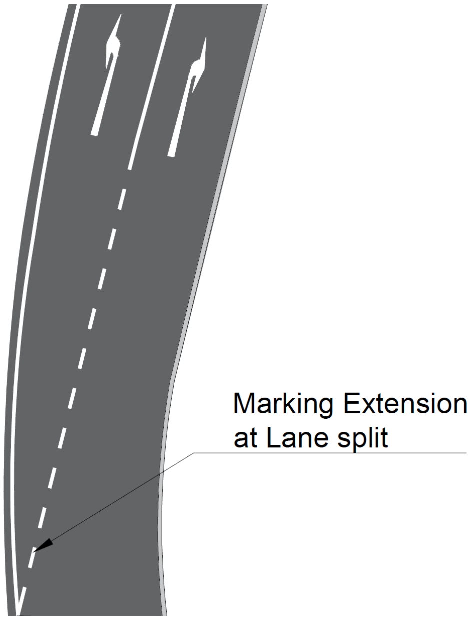


Figure 41: Yellow marking at lane split

Lane marking design

It was observed from the test drives that maintaining a befitting road marking design and quality at lane splits is crucial to disallow the fault deviation of the steering assist system. In some lane split designs in Espoo, e.g. Mankkaantie, lane extension markings do not fully separate left and right turns, which in many cases causes unintended lane departure. It was therefore recognized that marking extension at lane splits are essential to control the driving direction of the Autopilot, as shown in figure 42.



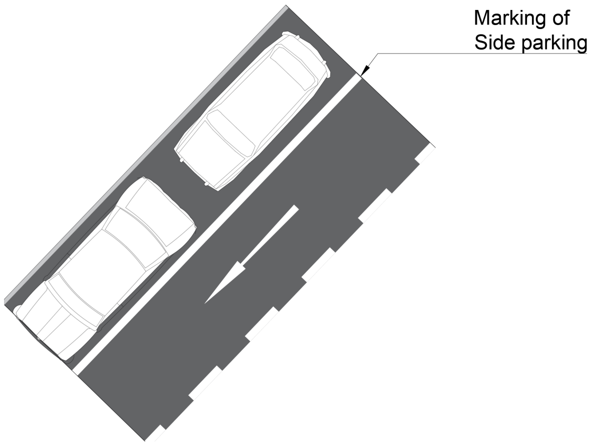


Figure 42: Marking extension at lane split

Figure 43: Marking of side parking spaces

In addition, it was also consistently observed from the road tests that vehicles parked on the side of the road, as shown in figure 36, causes Autopilot to stop unexpectedly, as it mistook parked vehicles for stopped traffic. However, this was indicated at road sections where there was no edge markings along the parking spaces, which caused Autopilot to not distinguish the lane's edge. It was therefore observed that the marking of side parkings is seen important for Autopilot's lane detection as shown in figure 43. Similarly, the stopped bus shown in figure 18 had caused the vehicle to stop in the middle of the road, as the bus's tire obstructed the detection of the edge marking. It was, therefore, observed that in situations, where neither a line marking, curb, or road shoulders are present on the edge of the road, the Autopilot system was not able to overtake stopped vehicles, even at wide roads where there is enough space for the vehicle to pass through.

Overall, based on road tests of several driving scenarios demonstrated above, Tesla's machine vision lane detection system seem to prioritize the recognition of road markings for lane centering when performing the dynamic steering assist tasks. Based on the trends of several lane departures and failures of Tesla's lane keeping system, it appears that 'continuous' (white or yellow) road markings are the most distinguishable design element for the lane detection system. After that, are dashed markings. If neither continuous or dashed markings are found on the road, machine vision seem to rely on curbs for lane keeping.

7 Conclusion

The final chapter will summarize the findings of the study and reflect on the reviewed literature within the scope of the research questions. The research problem is discussed in the light of our findings, and is explored within the broader planning challenge, which in this case is "the implications of automated vehicles on street design and planning".

The findings of this research indicate several elements in Espoo's street design that are seen significant with the emergence of AVs. The thesis partly demonstrates how the Tesla Autopilot uses machine vision for lane centering, primarily through lane markings but also through road curbs. The study assesses the automation ability of the Tesla Autopilot in the road network by experimenting several driving scenarios and weather conditions i.e. night and rain. The study also briefly tests other ADAS systems as a way to assess and compare the capabilities of other steering assist systems within similar road environments. Moreover, the study allows further exploration for the implications of AVs on road network planning and operation, in the short and long term, based on semi-structured discussions with two traffic and transport professionals in Finland.

It is expected that AVs will continue to rely on infrastructure to support its main driving tasks, including positioning, perception and navigation. However, different automation systems and use cases use different technologies, each with different sensing and fusion capabilities. Given much of this is still unknown, designing future road infrastructure will have its challenges. Today, the pertinent question to cities and road operators is whether physical and digital road infrastructure should evolve to support the operation of AVs. There have been some studies investigating the requirements for AVs to operate on road networks, (for example, (Austroads, 2017) and (Traficom, 2019)). The reports generally express challenges in providing practical guidance to road operators in a still evolving environment, and while some of the guidance may seem relevant, it may be beyond the scope of individual operators. However, based on the current technological trends in vehicle automation, road operators are advised to consider several physical infrastructure design and maintenance elements, including the machine readability of existing signs and line markings. Consequently, the consistency in design, implementation and maintenance of road markings are seen to have the most benefit in facilitating the deployment of AVs today. It can be observed today that the technology available in automated vehicles show different stages of development, and therefore, varying automation abilities in the street environment. In addition, different AV use cases are anticipated to introduce different requirements for the street design. In the future, cities should expect to have more heterogeneity with automation than today. Therefore, some agencies have considered the need to provide a framework, outlining where certain AV use cases should or should not operate in the road network.

While the study assesses several street design elements that are seen important for the operation of steering assist systems, operators are advised to consider frameworks and guidelines to plan for the introduction of AVs and other future street design implications. Therefore, it is important to consider other aspects of road operation and management when considering any new innovative changes in street design in the future. While the findings provide evidence for the implications that AVs may have on street design in the short term, other long-term implications for street design and planning are mentioned in the literature review of this study. In order to allow a more systematic street design and operation interventions to take place, the currently used approach of the conventional road hierarchy classification system may need to shift towards a more balanced ideology for the street network as a space for place and movement. Such ideology already exists within transport planning in Espoo; however, it may strategically appear fragmented from a road network operation perspective. This approach will allow cities to go beyond the traditional paradigms and look more holistically at the road asset as an operational system for multiple transport modes. This is expected to become more significant when AVs reach higher levels of automation and therefore cities should avert uncontrolled and unplanned deployments. In addition, cities should consider that while street design modifications could catalyze the deployment of AVs in the short-term, the pertinent question today is how such actions will shape cities in the long-term.

It is important to note that findings from the conducted road tests have only considered the operation of machine-vision based automated systems in clear, rainy, and night conditions. Further assessments for machine vision within other driving conditions, e.g. snow, may be needed to assess the ability of lane keeping and lane marking detection systems within existing snow maintenance conditions in Espoo. In addition, testing of other sensing technologies, including LiDar would allow further understanding of the ability and requirements of other automation systems for street design. More quantitative studies for the impact of different lane marking characteristics on machine readability, including width, position, reflectivity and luminosity will be necessitated if AVs continue to rely on road markings in the future.

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A Appendix - Survey results

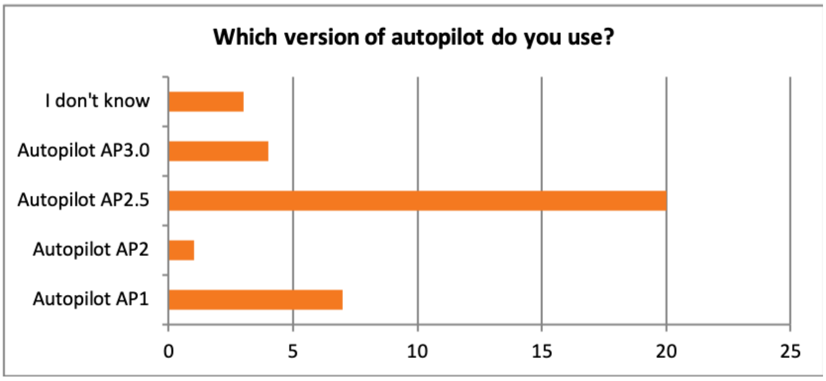

Figure 44: Autopilot users

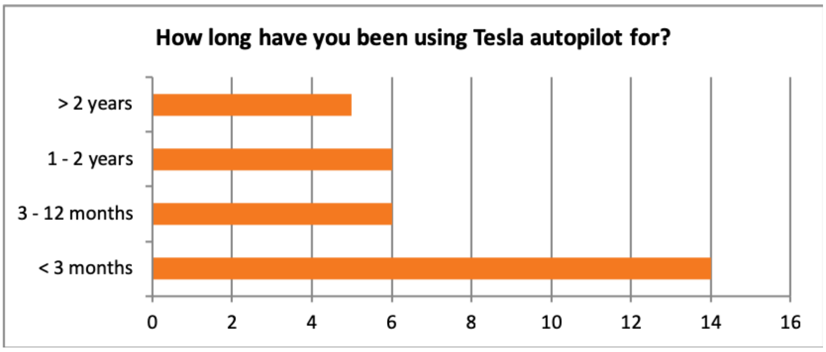

Figure 45: Users experience with Autopilot

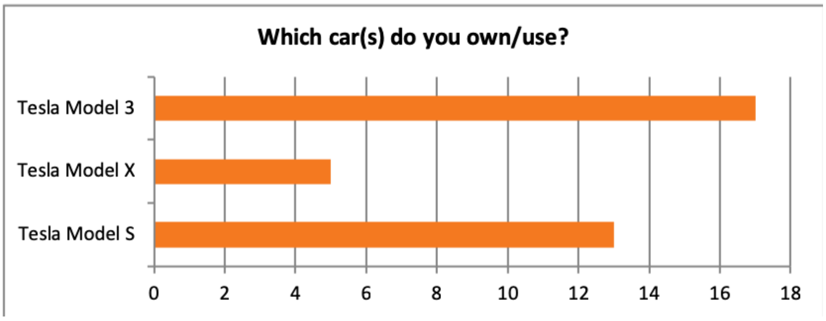

Figure 46: Tesla users car model

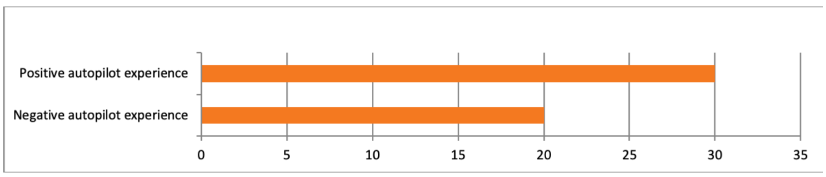

Figure 47: Users experiences

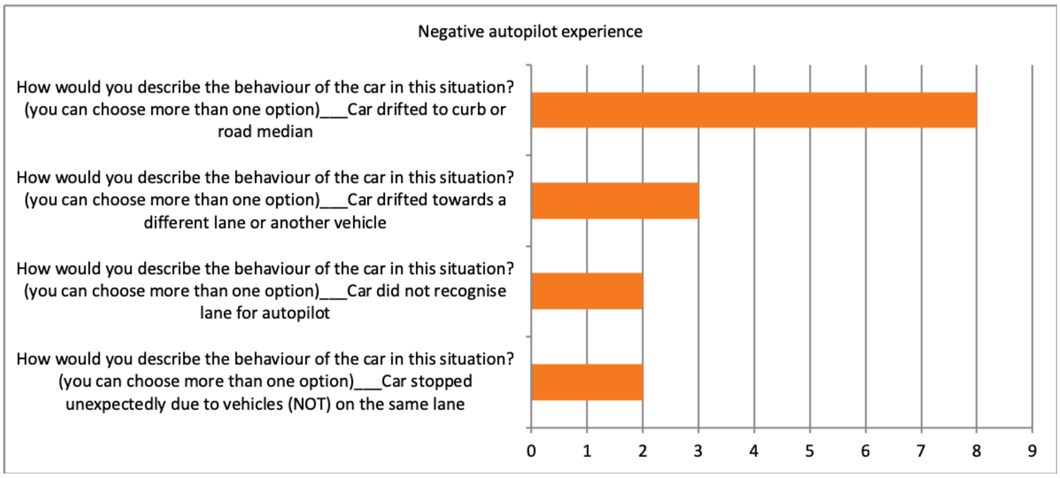

Figure 48: Users negative experiences with Autopilot

B Appendix - Test drives routes

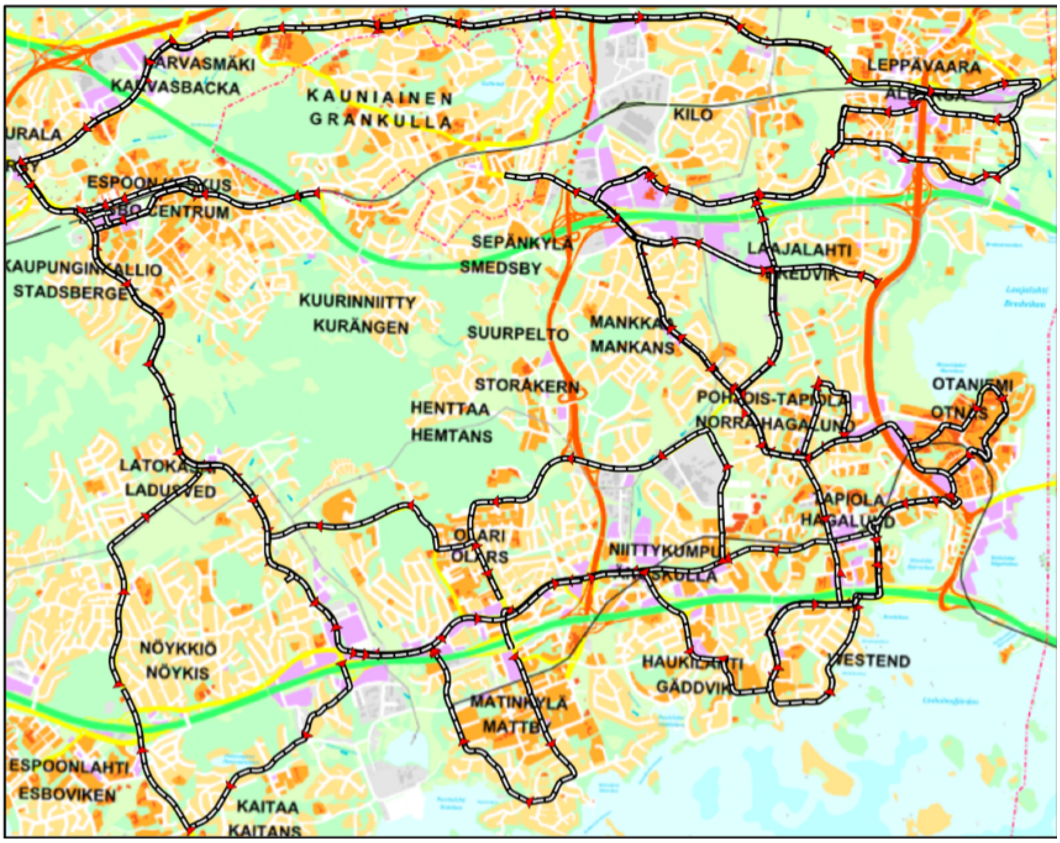

Figure 49: Test drive routes

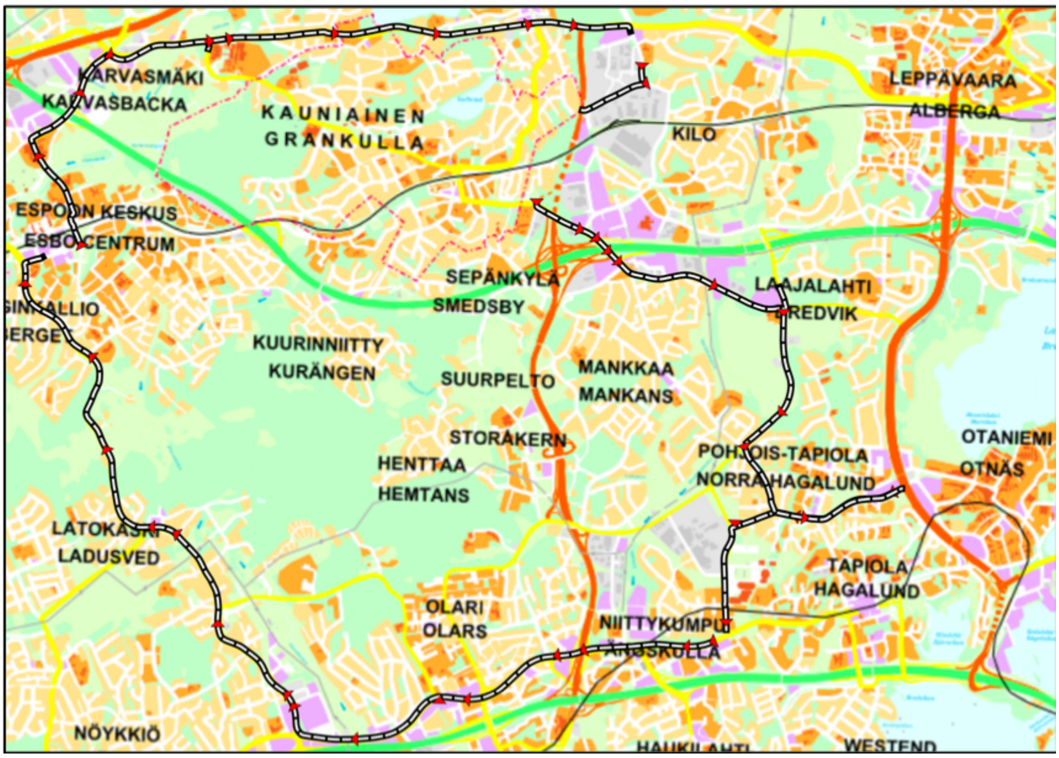

Figure 50: Rain test drive routes

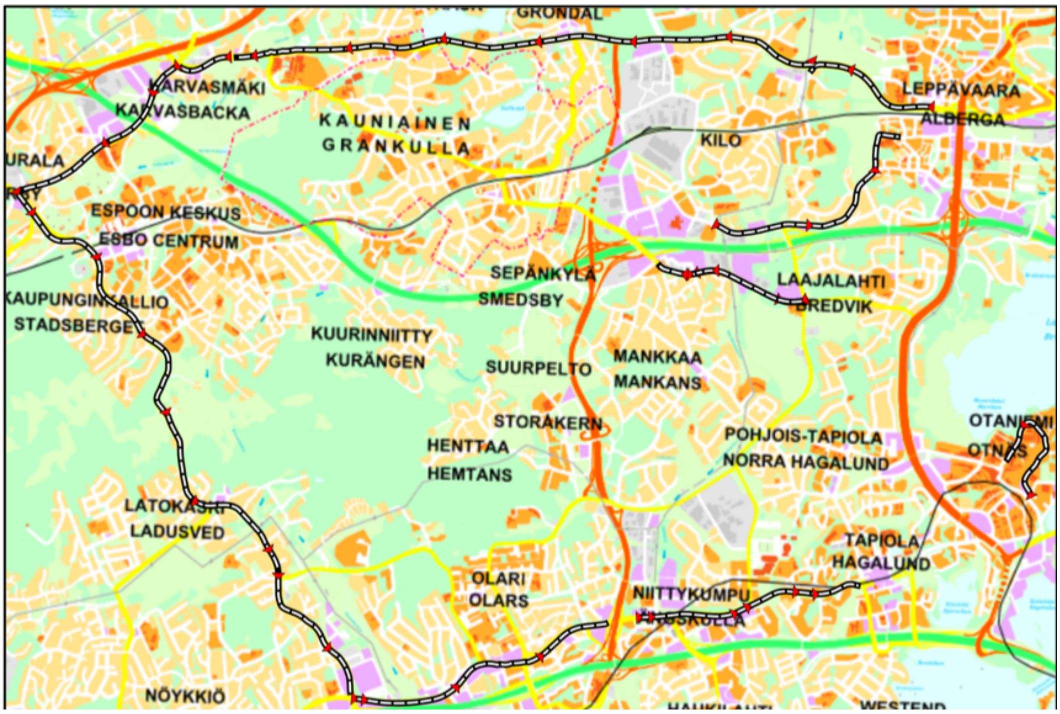

Figure 51: Night test drive route

C Appendix - Expert discussions

1. What are the current processes for defining changes in street design for AVs?

    Risto Kulmala: Automation technology is constantly going through changes and what might be applicable today is possible to not become relative in 2- or 3-years' time ...level 2 is quite trivial in a way, the car and road system should be okay for level 2 because it's the driver that has the responsibility of doing everything more or less. Except for the lateral and longitudinal control where the system is supporting, and the key word here is supporting.

    Eetu Pilli-Sihvola: Cities are expected to develop awareness of the situation to support the deployment of AVs and to avoid making decisions that may hinder the operation of AVs. . . so far I think the work with cities has been restricted to kind of planning for the automated shuttle operation because those are the ones that are taking place in cities. So far kind of, not yet any longer-term planning together (meaning with the national transport agency). I think partially because it's still unsure what actually the requirements will be. Today we can say that because they use the camera system that these are the issues but if you look 5 or 10 years ahead then there will be LiDar and they will use kind of multisensory approach then the problems will be different, and then the vehicles won't be so restricted in having the lane markings...but there is still very little that we kind of can say at any certainty about how cities should prepare for automated vehicles, so there is so much uncertainty on kind of how quickly the technology will become more common and what types of vehicles will be used... if just shuttles at low speeds then of course it's kind of different the requirements are not that kind of big and then passenger cars on one hand. . . It's good for cities right now to be actively listening and for the lookout for what is best awareness of the situation right now but what are the things that if you do those that at least it won't hinder the use of AVs.

2. What are the existing street design features that should be reconsidered?

    Risto Kulmala: In the short term It's mostly the temporary road design features like road work. . . today they are the ones that the automated vehicles cannot cope with really because there is no standardized way of marking them. . . in the medium term then you should start thinking about those that if you have a highly automated driving system, where the system can be capable of transporting you and you can read the newspaper, and then suddenly it reaches the end of the ODD then it has to park itself, then there be a safe parking space..

    Eetu Pilli-Sihvola: I think the general thing is that the better lane markings you have the kind of easier it is regarding automated vehicles... for example left turns in urban environment are extremely extremely difficult for any automated vehicles right now. I mean short term if you want to look at how to plan routes for automated vehicles or maybe guide them through the city you would go as far right turn only, kind of best practice from the logistics field…wide crossings is also a problem for the current technology, if you have high speed bikes at certain intersections, those are very difficult for the vehicle sensors only to pick-up...Interaction between AVs and bikes … is one critical aspects it can be already taken into account... Often there is also the discussion whether there should be kind of separate lanes for automated vehicles…it's hard to kind of recommend that as a best practice for any city if you try to look kind of at the big picture at the same time…it's not very realistic in most cases in cities so I also don't see that as kind of option on a wider scale… even though it will be easier for the vehicles and their operation maybe it can be bad from the transport system point of view…

(Regarding critical testing scenarios) Eetu suggested investigating design elements including: Lane narrowing and widening, types of marking at sections e.g. lane merge, lane split, bus stops, winter maintenance, shadows and sun light effect on machine vision.

3. What should be changed in road operation and maintenance?

Risto Kulmala: …for systems using cameras like tesla, for them the road markings are extremely important then you have to focus on maintaining the quality and visibility of the road markings and get rid of the confusing road markings…until vehicles can operate in snowy and icy conditions so if we want to have a highly automated vehicle to operate also in those conditions so we have to have more effective winter maintenance so that they clearing the snow of the road and ice that everything is visible over there and the vehicle can operate safely but its costly…

Eetu Pilli-Sihvola: I think one pretty obvious change in maintenance at least in the short term maybe in the medium term is requirements for winter maintenance which kind of come from the requirement to have visible lane markings for systems that use cameras so that is something is pretty safe for saying that at least for highways or main roads, that is kind of a big thing if you want people to be able to use AV autopilot or automated system on those roads…

4. What are the important sensors and infrastructure needed in the vehicle and roadside?

Eetu Pilli-Sihvola: …the basic problem is that it's expensive to maintain. If you have something specific for example helping AVs to localise themselves more accurately and if you have to have that on the whole main road network for example; its really expensive to have built and maintain there, so it's not very high on the list of priorities I would say, because the basic concept also from the manufacture side is that the vehicle has to survive by itself using the sensors it has and the processing capabilities it has…the Finnish approach is that we want any solution to be tech neutral, we don't want to take sides, if there are regulations by EU for example, we need to provide other tech as well. No sides regarding the technology, so we can have even playing fields for all types of solutions...

5. What are other aspects to be considered in planning, management and operation of AVs?

   Risto Kulmala: I think the concept of separation of road users has to be rethought so where you want to have those common space... some vehicle manufacturers are not happy to have bicyclists in the same road way, that would mean that with all those nice plans where they are talking about the common space it would not work perfectly well with such automated vehicles...we should have all the traffic management information be digitally available, so that automated vehicles should know what rules and regulations apply to a certain place what are the properties of this connection and how they are related to their routes and destinations and specially if they want to pick up the route to their destination, like this sort of geofencing restriction information should be there and likely geofencing information should include information of the ODD where it can be operated in the automated car modes...ODD will be more important than automation levels, it kind of need to be much more specific in defining the ODDs and in a way that its easy for the users also to understand the limitations... through standards or some other kind of collaboration there need to be work on finding the best group of ODDs for the different systems...

   Eetu Pilli-Sihvola: The best approach for cities now is to develop awareness towards the aspects of street design that are seen to hinder the performance of automated systems now and in the future. For example, roundabouts are seen to work better than regular 4-leg intersections due to lower number of conflict points.